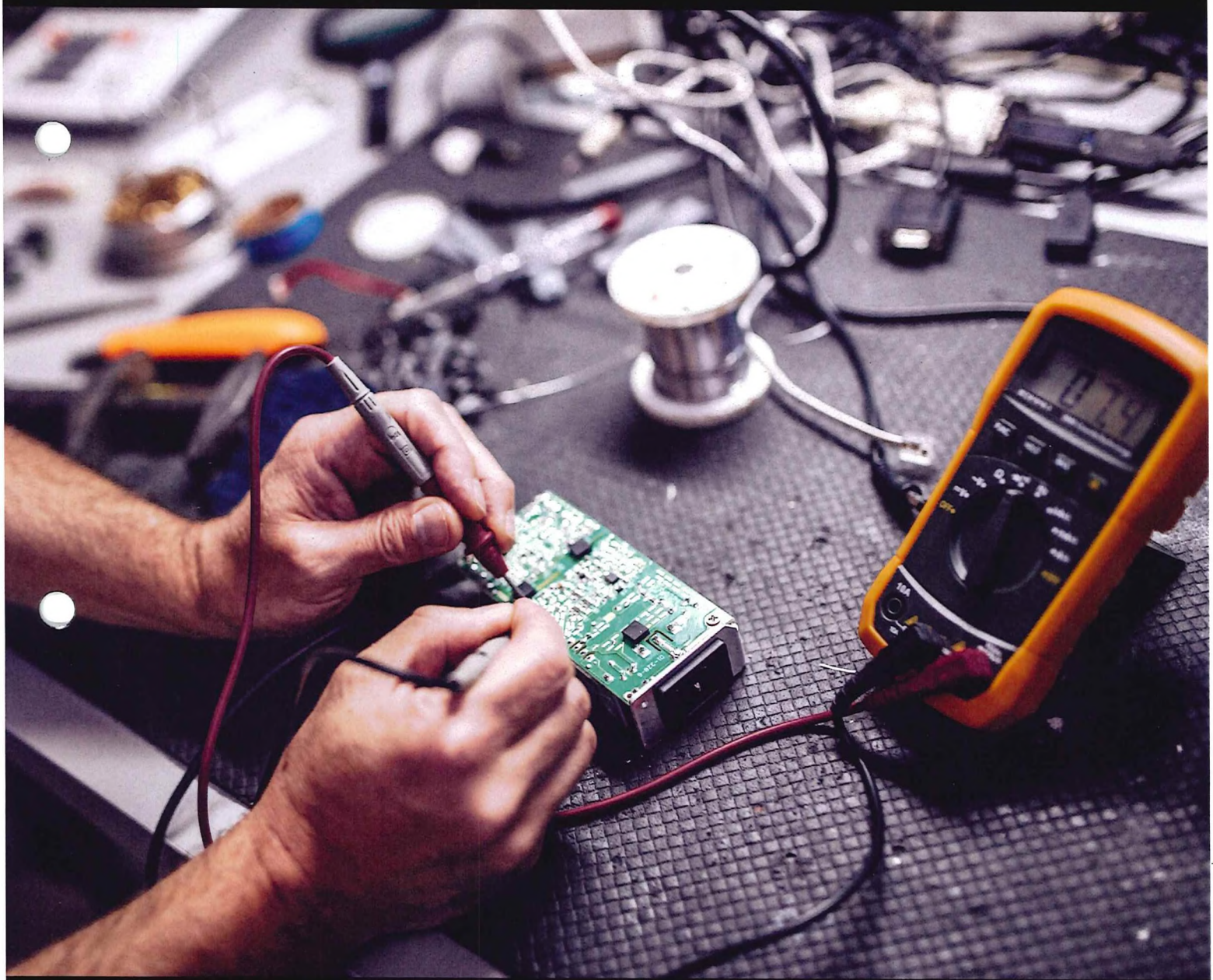
TAFE NSW

Power supply principles



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Learner Resource

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Power Supply Principles

Version 2 - March 2022

The Electronics Section
Ultimo Campus of TAFE NSW
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Ultimo NSW 2007

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Introduction

This workbook has been written to help students satisfy the assessment requirements for the following Unit:

- UEEEC0075 - Troubleshoot single phase input DC power supplies

More information about electrotechnology training packages and the above Units can be found at www.training.gov.au/home/tga. Type the course/unit number in the "Quick search" and press return.

Textbooks

The following textbooks can be used to supplement the notes in this workbook. Most (if not all) of these books are available from the library in Building D.

- Beards (1996). *Analog and digital electronics: A first course* (2nd edition). Prentice Hall.
- Boylestad & Nashelsky (2002). *Electronic devices and circuit theory* (8th edition). Prentice Hall.
- Davis (1996). *Understanding DC Power Supplies and Oscillators*. Prentice Hall.
- Edwards & Myer (1993). *Electronics; a basic course* (2nd edition). McGraw Hill.
- Floyd (2002). *Electronic devices* (6th edition). Prentice Hall.
- Gates (2001). *Introduction to electronics* (4th edition). Thompson Printing.
- Metzger (1998). *Electronics pocket handbook* (3rd edition). Prentice Hall.
- Morris (1997). *Applied electronics*. Arnold Publishing.
- Paynter & Boydell (2002). *Electronics Technology Fundamentals*. Prentice Hall.
- Phillips (1998). *Basic electronics: an introduction to the fascinating world of electronics*. FPC Magazines. [Note: This is a magazine and can only be purchased from Jaycar.]

Lesson organiser

Lesson	Section	Topics and activities
Before starting (ideally)	Required reading	■ Workplace Health & Safety ■ Using sustainable energy practices ■ Communication and documentation ■ Test and measurement devices ■ Transformer efficiency (losses) and turns ratio
1	1	■ Diode junction characteristics ■ Diode operation in simple DC circuits ■ Practise testing diodes using a DMM ■ Practise measuring diode forward and reverse bias operating conditions using a simple DC circuit
2	2	■ Power supply operating principles & applications ■ Half-wave rectification ■ Practise measuring diode operating conditions in half-wave rectifier circuits (both functional and faulty) using an AMM and an oscilloscope
3	3	■ Full-wave rectification ■ Practise measuring diode operating conditions in full-wave rectifier circuits (both functional and faulty) using a DMM and an oscilloscope
4	4	■ Filtering (smoothing) ■ Practise measuring key potential differences (including ripple) in filtered half-wave rectifier and filtered full-wave rectifier circuits using a DMM and an oscilloscope
5	5	■ Dual rail power supplies ■ Fault-finding unregulated power supplies ■ Practise measuring key potential differences around faulty unregulated power supplies to identify the likely faulty component and what is wrong with it
6	6	■ Regulation ■ Practise measuring the output voltage and load current of unloaded and loaded unregulated power supply circuits using a DMM and an oscilloscope
7	7	■ The zener diode shunt regulator ■ Practise measuring the output voltage of loaded shunt regulator power supply circuits using a DMM and an oscilloscope
8	8	■ The 3-terminal regulator IC ■ Practise measuring the output voltage of loaded 3-terminal regulator power supply circuits using a DMM
9	■ **Assessments - Refer to UAG for details**	

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Student notes

Required reading

Purpose These notes are provided to support your revision on aspects of this Unit that have been taught before in other Units (typically more than once) and will not be taught again but may be assessed.

This issue is explained in more detail on the following pages.

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Introduction

As you probably know, *units of competence* that make up qualifications in the Electrotechnology Training Package (like CIII Electronics and Communications) prescribe what must be taught and assessed.

This is done using *elements of competence* together with *performance criteria* for each element. More detail on these is provided in the *assessment requirements* for the unit using two lists: one is the list of *performance evidence*; and the other is the list of *knowledge evidence*.

There are some performance criteria (together with performance evidence and/or knowledge evidence in the assessment requirements) that appear in many units and these include items on the following topics:

- work health and safety (WHS)
- using sustainable energy practices
- the appropriate use and completion of documentation
- appropriate communication with supervisors, customers and other stakeholders.

It makes sense that these performance criteria are common to multiple units because, taking WHS as an example, it's not reasonable to claim competence when the work was completed successfully but in an unsafe way.

As well as the topics listed above, there are performance criteria and/or assessment requirements related to electrical/electronic theory and practice that appear in two or more units. This occurs when the people who have developed the training package (not TAFE NSW) have decided that it's appropriate that they should do so. An example of this for UEEEC0075 is the requirement for you to demonstrate knowledge of transformer turns ratio and losses which you have previously learnt about when undertaking EC0074 (formerly UEENEEH114A).

Importantly, where all these topics have been comprehensively taught before, it is usually unnecessary to teach them a second or third time. That said, we are still expected to ask you to provide knowledge evidence and/or performance evidence possibly by answering questions on these topics in the theory test and/or demonstrating your skills on these topics during the practical tests.

For this reason, the following information and/or notes are provided for you to read and use to ensure that you can satisfy the assessment requirements for this unit.

Work health and safety (WHS)

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0075), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to WHS and their associated knowledge evidence and performance evidence:

1.1 - Work health and safety (WHS) procedures for a given work area are obtained and applied (UEECD0007 references: 1.2, 1.3 & 1.4)

2.1 - WHS risk control work measures and workplace procedures are followed (UEECD0007 references: 1.4, 1.6, 2.1 and 2.4)

3.1 - WHS risk control measures and workplace procedures for work completion are followed (UEECD0007 references: 3.1 to 3.4)

3.2 - Worksite is cleaned and made safe in accordance with workplace procedures (UEECD0007 references: 2.6)

Source: https://training.gov.au/Training/Details/UEEEC0075

As you may already be aware:

- WHS is taught and assessed in a dedicated unit, CD0007 (formerly E101A)
- CD0007 or E101A is a pre-requisite unit for undertaking EC0075 (that is, you must have successfully completed CD0007 or E101A to be able to undertake EC0075)
- The performance criteria listed above are underpinned by, and/or are identical in substance to, the performance criteria from CD0007 and E101A indicated in the brackets above
- You have successfully met the assessment requirements for at least one or more of the following units which also include the performance criteria listed above: EC0066/H113A, EC0067/H139A, EC0069/H112A and EC0074/H114A.

Importantly, the knowledge and skills needed to perform these performance criteria are identical to those needed to repair resonance, amplifier and digital circuits operated from mains. This means that you already have the ability to demonstrate your knowledge of, and demonstrate your ability to carry out, these performance criteria in the context of this unit.

However, if your unsure and would like to read more information about these performance criteria, please refer to your learner resources for CD0007/E101A that specifically address them.

Note: If you have not successfully completed CD0007 or E101A, please bring this to the urgent attention of the teacher before undertaking any of the simulated workplace tasks.

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Using sustainable energy practices

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0075), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criterion:

2.3 - Fault-finding activities are carried out efficiently without unnecessary waste of materials, or damage to apparatus, the surrounding environment or services using sustainable energy practices.

This includes knowing about sustainable energy principles and using sustainable energy practices.

Sustainability is a much used word now that describes growing global response to the short and long term negative effects on the planet of certain human activities, particularly in relation to climate change and pollution. It's accepted that, without drastic action, both problems will likely make living on this planet more difficult (due to extreme weather and toxic environments) that, in turn, risk causing drought, famine, war and the failure of democratic governments and even whole nation states.

R J Fuller (Deakin University, 2005) describes four principles that underpin sustainability:

- Futurity - The concern for future generations
- Environment - The concern to protect the integrity of eco-systems
- Equity - The concern for the poor and disadvantaged
- Participation - The notion that individuals can participate in decisions affecting them

An essential element of the global response to climate change is the switch to sustainable energy. Energy is said to be sustainable if it "meets the needs of the present without compromising the ability of future generations to meet their own needs." Underpinning this are the sustainable energy principles which include (but are not limited to):

- Reducing our use of non-renewable energy sources (like the fossils fuels which includes coal, gas and oil)
- Increasing our use of renewable sustainable energy sources (like solar just to name one of many)

Fuller's fourth principle is important because it means that individuals, including you, can contribute directly and indirectly to sustainable energy principles by using sustainable energy practices where possible. Direct action that can be taken includes (but is not limited to):

- Switching off equipment not in use
- Turning off lights when leaving a room with nobody in it
- Opening windows to cool rooms instead of turning on room air-conditioning
- Using natural lighting
- Minimising waste
- Recycling waste
- Using public transport to and from work
- Drinking tap water

Indirect action that can be taken, includes (but is not limited to) encouraging your employer to:

- Using more energy efficient lighting
- Using more energy efficient equipment
- Reducing (in winter) and increasing (in summer) the temperature setting of air conditioning so that to uses less energy
- Switching to using sustainably sourced and/or sustainably manufactured materials
- Switching to an SEU energy provider

With all that said, every workplace is different so what works with one may not work with another.

Communication and documentation

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0075), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to workplace communication and documentation and their associated knowledge evidence and performance evidence:

1.3 - Advice is sought from work supervisor to ensure work is coordinated effectively with others

1.4 - Materials required for the work are determined in accordance with workplace procedures

1.5 - Tools, equipment and testing devices required to carry out the work are obtained in accordance with workplace procedures and checked for correct operation and safety.

3.3 - Justification for solutions used to resolve single phase input DC power supply problems are documented in accordance with workplace procedures

3.4 - Work completion is documented and appropriate person/s notified in accordance with workplace procedures

The specific knowledge required to satisfy these performance criteria is specific to each workplace setting. However, the skills are generic and so are transferable between workplace settings including simulated workplace settings at TAFE NSW. This means that, when you undertake the in-class simulated workplace tasks and the practical test, you are expected to demonstrate your skills in this regard.

Importantly, while undertaking the in-class simulated workplace tasks and/or the practical test for this unit at TAFE NSW, the following applies to key terms in the performance criteria above:

- "Workplace supervisor" refers to the class teacher
- "Others" refers to the class teacher and other students in the class
- "Materials" refers to components and training aids needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list
- "Workplace procedures" refer to the written and verbal procedures and instructions provided by the teacher for the safe and proper conduct of skill practise exercises
- "Tools, equipment and testing devices" refers to tools and test equipment needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list and/or mounted on the workbenches
- "Documented... in accordance with workplace procedures" refers to the requirement for students to record their measurements, other results, and answers to questions on the skill practice exercises and/or any handouts that must be submitted to the teacher.

The following is the procedural requirement for undertaking the simulated workplace tasks that form the basis of skill practise exercises.

- Students must have permission from the teacher to start every skill practice exercise.
- Students must work individually on every skill practise exercise, or in pairs with the permission of the teacher (but never more than two per group).
- Students must perform a WHS risk assessment at the start of every skill practice exercise to ensure the safety of themselves and others.
- Students are to bring to the attention of the teacher any hazards that they identify for which there are they cannot implement appropriate control measures.
- Students are to collect equipment from the trolley in a safe and orderly manner having respect for the reasonable needs of other students.
- Students are to follow the written instructions in every skill practice exercises in correct order and in total including any qualifying notes.
- Students are expected to record their measurements, other results and answers to questions for every skill practice exercise and/or any handouts that must be submitted to the teacher.
- Students are expected to call the teacher to check their work when instructions direct them to do so.
- Students are expected to retake any measurements and reattempt and/or correct any of their answers to questions when reasonably directed to do so by the teacher.
- Students are not to return their equipment to the trolley or leave **until** they have completed the skill practice exercise and their work has been checked by the teacher.
- Students are expected to submit their work to the teacher by the due date when required to do so.
- At the completion of every skill practice exercise, students are expected to return all equipment to the trolley tidily (unless directed otherwise by the teacher) and ensure that the workspace is left cleaned and safe.
- Students are to bring to the attention of the teacher any faulty test equipment, tools and components.

Test and measurement devices (also known as test equipment)

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0075), you're expected to demonstrate your knowledge of:

- Electronic testing and measuring devices and techniques including:
  - test/measuring devices and their application including:
    - multimeters
    - signal generators [sic] and oscilloscopes
    - voltage and digital tests [sic]
  - connection of test/measruing devices into a circuit including:
    - ensuring circuits are isolated
    - testing or measuring on live and operating system safely
    - circuit arrangement of test/measuring devices
  - taking readings
  - storage, maintenance and care of test/measuring devices.

In addition, you must demonstrate your ability to:

- Take measurements correctly and accurately.

You first learnt about multimeters when undertaking unit CD0043 and oscilloscopes when undertaking unit EC0074. Moreover, you have practised using this test equipment extensively when undertaking simulated workplace tasks for these and other units (including EC0066 and EC0067).

However, if your unsure that you are able to demonstrate your knowledge of these tasks or your ability to carry them out, the following notes have been provided here for your convenience for you to read.

Types of test and measurement devices
Three types of test equipment commonly used when fault-finding electronics equipment include:

- Multimeters
- Signal generators
- Oscilloscopes

Of these, two are used when fault-finding DC power supplies: multimeters, oscilloscopes and dummy loads.

Multimeters are three (and even more) instruments in one consisting of at least:

- a voltmeter for measuring potential differences
- an ammeter for measuring circuit current
- an ohmmeter for measuring the resistance of components, particularly resistors.

Voltmeters are useful when fault-finding DC power supplies because they can be used to measure average and effective potential differences (also called voltages) around the circuit for comparison to predicted values to determine whether there is a fault. Then, when a circuit is found to be faulty, the difference between the measured and predicted voltages can be used to determine what component is faulty and possibly even predict what is wrong with it.

Ammeters are useful when fault-finding DC power supplies because they can be used to measure the effective load current to determine whether the load is drawing too much current and whether the power supply's full-load current performance matches the specification.

Ohmmeters are useful when fault-finding DC power supplies because they can be used to measure the resistance of suspect components like resistors and to identify short-circuit component terminals. They can also be used for cold-testing of circuits when looking for short-circuits.

Oscilloscopes are effectively voltmeters that also show the shape of the voltage. When observing AC voltages, the oscilloscope can also measure the period and frequency (either indirectly or directly) of the voltage.

Oscilloscope are useful when fault-finding DC power supplies because they can be used to determine the size and frequency of the ripple voltage on the output. These can be compared to predicted values to determine whether the DC power supply is faulty and possibly what component is faulty.

Dummy loads
A dummy load is another piece of test equipment that you have probably used before though you may not have heard of this term. It's a fixed resistor or variable resistor that is connected to the output of a circuit like an amplifier or power supply in place of the device or circuit that is usually connected to their output. For amplifiers, this allows the technician to perform tests without having to listen to the test signal because the dummy load replaces the speaker. For power supplies, the dummy load is used to set the amount of current drawn from the power supply to test performance attributes like *load regulation* and *full-load current.*

Safety considerations when connecting test and measurement devices to circuits
When using a multimeter or oscilloscope to test and measure electronics equipment, there are two important safety measures that can minimise the risk of your being fatally electrocuted.

The first relates to the fact that technicians usually must necessarily test mains-operated electronics equipment (like a hi-fi or PVR) that is plugged-in, turned on and operating. To minimise the risk of electrocution, you must ensure that the equipment that you're testing or repairing is plugged into a power point that is protected at the switchboard by a residual current device (RCD). You can check whether the building's powerpoints are RCD protected by looking inside the switchboard. Figure 1 below shows an example of what to look for.

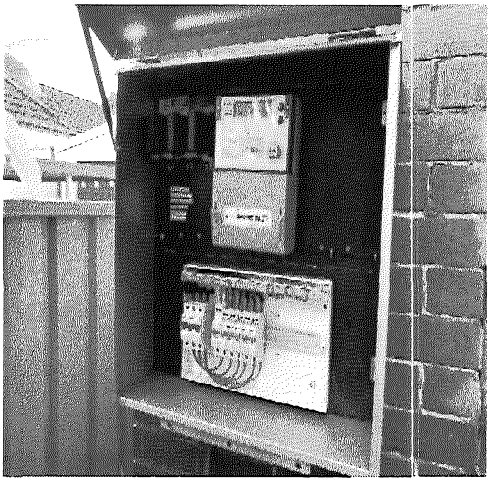

Figure 1

Up close, RCDs look like the example in Figure 2 below and there should be at least one row of these devices in the switchboard mounted side-by-side. RCDs are easily recognised by the fact that they're switched devices and often they have an in-built test feature too.

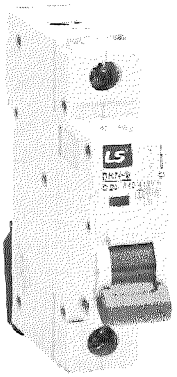

Figure 2

RCDs have been designed expressly for the purpose of preventing people and animals from a sustained direct connection to mains which can be fatal.

If the switchboard is older it may use semi-enclosed cartridge fuses instead of RCDs and an example is shown in Figure 3 below. Importantly, being fuses, these devices are designed to protect equipment and prevent fires but they **do not** prevent people/animals from potentially fatal electrocution. You should avoid powering the equipment that you're testing/reparing from power points that are only protected at the switchboard by these fuses.

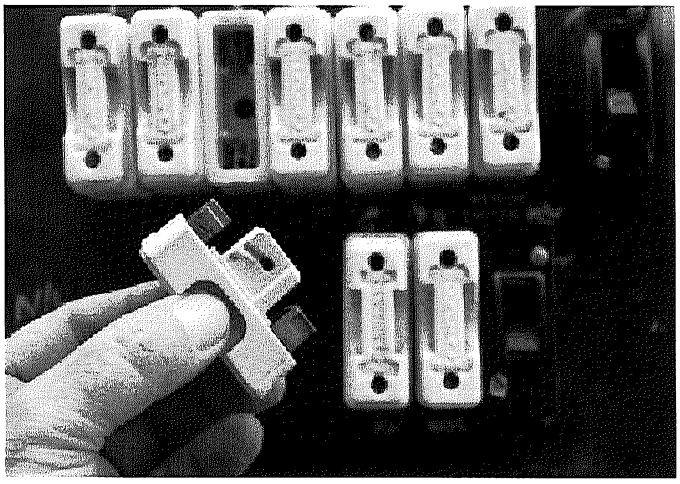

Figure 3

If you can't access the switchboard to see what's inside, or you know for certain that the power point is not RCD protected, then plug the equipment that you're testing into the powerpoint of a powerboard that is RCD protected instead. An example is shown in Figure 4 below - Notice the RCD at the left end (which includes a button for the test feature).

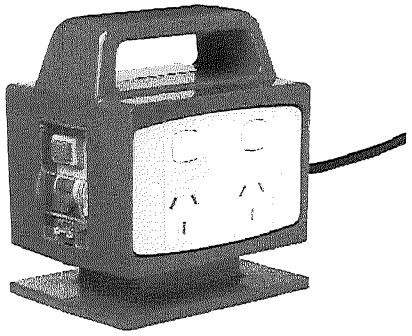

Figure 4

Take care when purchasing protected powerboards because there are many that offer "surge" and/or "overload" protection. While these features are useful, they don't provide protection from electrocution. Powerboards that are RCD protected will state this clearly and are usually a fair bit more expensive than simple surge and overload protected powerboards.

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The second safety measure you must employ when connecting multimeters to live equipment, involves never doing so with your fingers touching any of the probe's metal parts. Figure 5 below shows the correct way to hold the probes. Notice that the person holds the probes behind the their slip barriers.

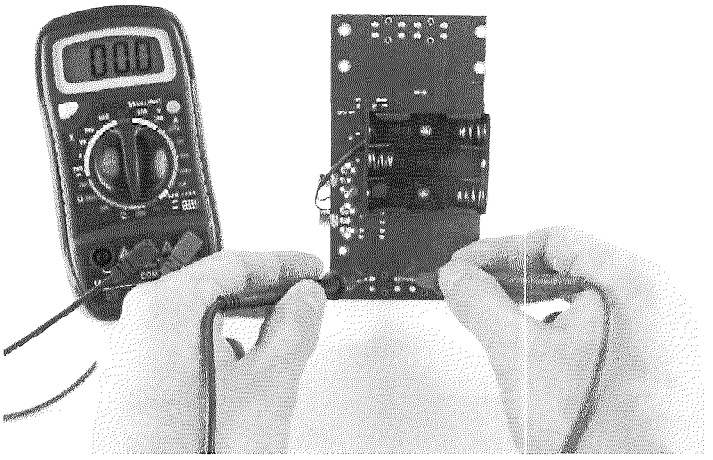

Figure 5

Connection of test and measurement devices to take measurements correctly and accurately
When measuring potential differences, the voltmeter is connected to the circuit in parallel with the component whose potential difference you want to measure. This is shown in Figure 6 below using a simple series circuit consisting of a resistor and a lamp with the meter measuring the potential difference across the resistor. The meter is shown both as a drawing (on the left) and as a schematic symbol (on the right).

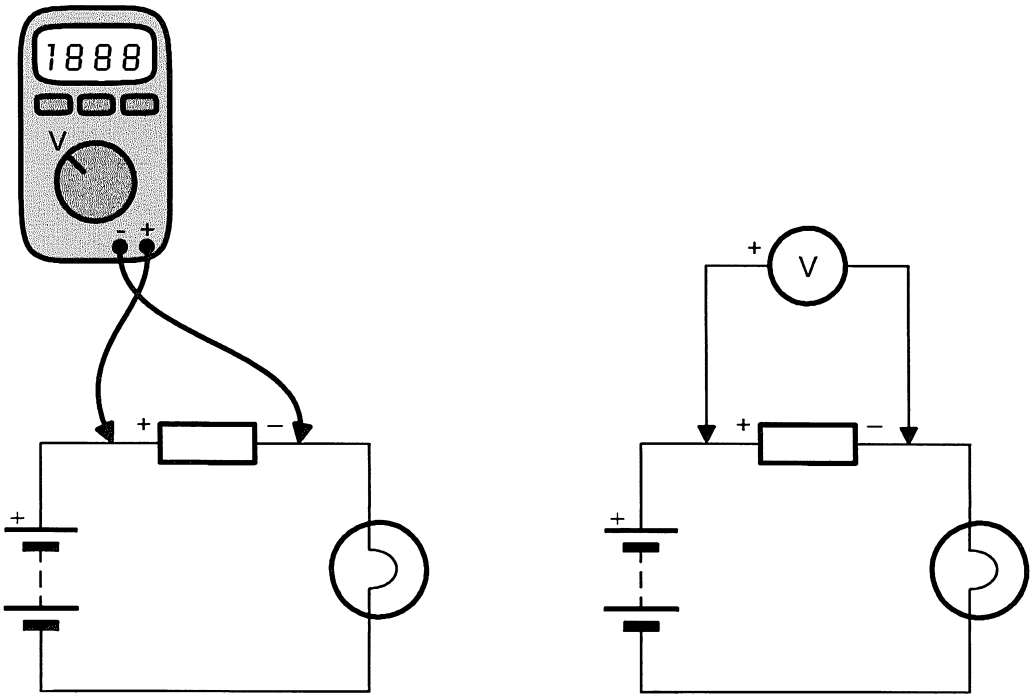

Figure 6

Notice that the voltmeter's positive probe must be connected to the potential difference's positive side. So, you must determine which side of the component is positive before you connect the meter. The simple rule for this involves recalling that, for all components except the EMF, the side of the potential difference that is positive is the side that conventional current enters the component.

Care must be taken when connecting the meter to the circuit so that you don't actually short two points of the circuit together. This is especially a risk when measuring the voltage on the leads of transistors and the pins of integrated circuits because they're so close together.

Care must also be taken to read the meter's readout correctly so that you notice the position of the decimal point and notice whether the measurement is in volts or millivolts. This would be indicated to you on the meter's readout (which would show either V or mV).

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When measuring currents, the ammeter is connected to the circuit in series with the component whose current you want to measure. This is shown in Figure 7 below using a simple series circuit consisting of a resistor and a lamp with the meter measuring the current through the resistor (which is also the current through the lamp in this case because it's a series circuit). The meter is shown both as a drawing (on the left) and as a schematic symbol (on the right).

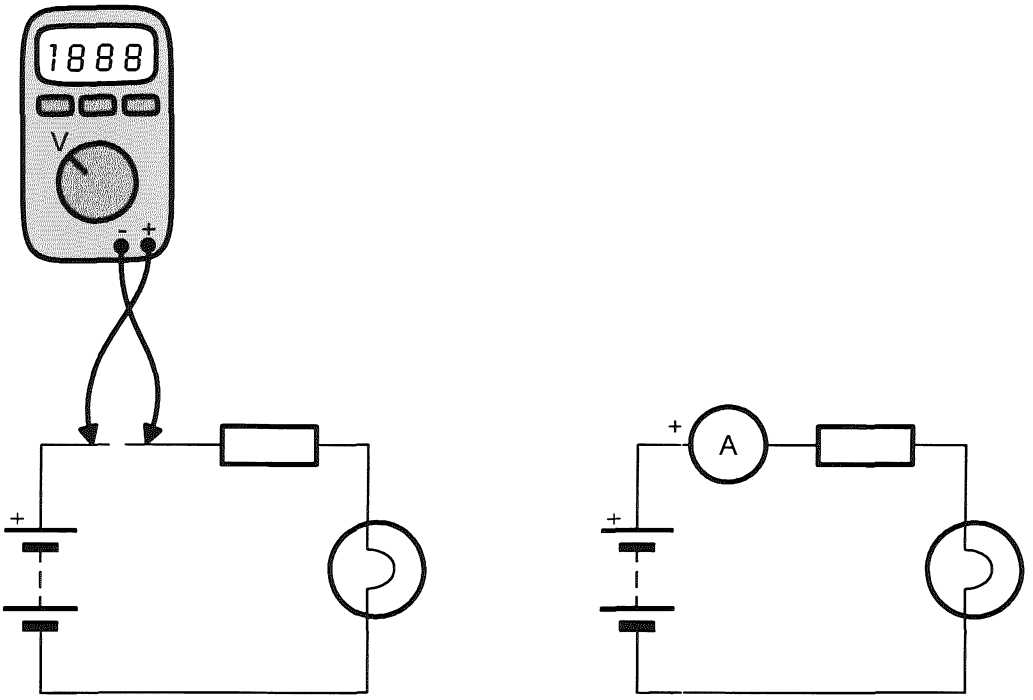

Figure 7

Notice that the circuit must be broken at some point to introduce the ammeter (an inconvenience that limits the practical measurement of current in the workplace). Notice also that the ammeter's positive probe must be connected to the point in the circuit from which the conventional current flows.

Care must be taken to read the meter's readout correctly so that you notice the position of the decimal point and notice whether the measurement is in amps, milliamps or even microamps. This would be indicated to you on the meter's readout (which would show either A, mA or μA).

Measuring resistance is a simple matter of connecting the meter's probes across the component in any polarity as shown in Figures 8 below. Importantly though, recall that the component should be removed from the circuit before you make the measurement.

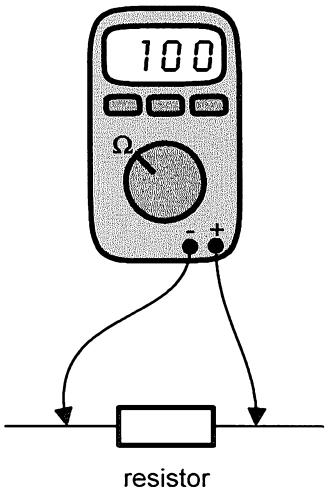

Figure 8a

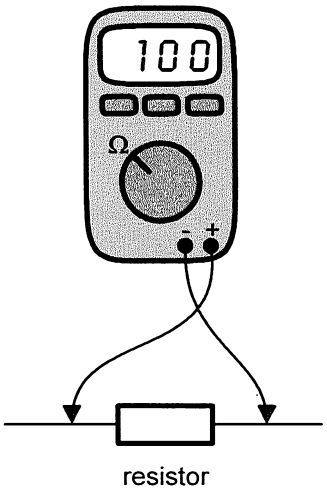

Figure 8b

Also remember that your fingers should not be touching the metal parts of the probes. If the component is out of the circuit, you're not going to get electrocuted. However, if you're touching the metal parts of both probes, the ohmmeter may show an incorrect resistance for the component because the measurement will include your bodily resistance.

Storage, maintenance and care of test and measurement devices
To ensure the longevity of test and measurement devices and their optimal performance (especially accuracy), there are storage, maintenance and care practises that you should follow. This is especially important when using test equipment to check and/or repair electronics equipment that is used to in applications and/or environments where degraded or faulty performance can ultimately put life and property in jeopardy (examples include the check and/or repair of medical equipment, military equipment, and equipment used in the mining and petrochemical industries, just to name a few).

In terms of the storage of test and measurement devices, there are a few simple practises to follow:

- Keep test equipment dry

  As it's unsafe to work on live electronics equipment in wet conditions, it makes sense that test and measurement devices are usually not waterproof (though, they may be water resistant). So they must be kept dry to avoid degraded performance and failure.

- Keep test equipment free from knocks

  Digital multimeters (DMMs) are designed these days to withstand use on building sites by electricians who may often work at heights and so they're pretty tough. Moreover, protection is often further enhanced by rubber surrounds. With that said, DMMs can still be damaged in storage if they're stowed in a vehicle and not secured properly together with other tools and equipment that also not secured properly. Sudden breaking can force objects to accelerate up to very high speeds at short distances. The unprotected parts of the DMM's casing and display are particularly vulnerable to damage when striking sharp edges with force.

  Importantly, most oscilloscopes are not intended to be portable and so they will not be designed to be as tough as DMMs. As such, they can be damaged from knocks and drops from even small heights and this should be avoided altogether.

- Keep test equipment free from vibrations

  Vibrations are problematic because, over time, they can cause mechanical parts (for example, nuts on bolts) to loosen and they can cause materials to fatigue and fail at fixing points. You've probably seen this in action yourself if you have ever broken a piece of metal simply by bending it back and forth for a time.

- Avoid stacking test equipment

  Test equipment are usually not designed to be stacked in the first instance and so the case will have relatively low weight-bearing capacity that, if exceeded can, readily cause warping to the case and damage to internal parts.

- Avoid storage at high temperatures

  This may come as a surprise but all electronics components have a maximum temperature at which they can be stored and operate reliably when in use. The figure varies between components but a typical maximum is 150°C. More sensitive components like LCDs will have maximum ratings that are much less than that (as low as 60°C).

  While these sort of temperatures seems high enough for most storage applications inside a building, the internal temperature of a vehicle parked in sunlight on a hot summer's day can easily exceed 60°C. Self-storage units are often very exposed (ie zero shade) and so the temperatures inside can range between 55°C and 85°C on a hot summer's day. These temperatures can damage sensitive components in electronics equipment.

- Avoid storage at low temperatures

  Many electronics components can be stored to temperatures as low as -50°C and LCDs down to -20°C. This might seem satisfactory for most of the planet but even here things aren't quite what they seem. Humid air inside the equipment's case will assist condensation if the equipment cools. Once water droplets have formed inside the casing, they can cause corrosion and short-circuits.

- Remove batteries when equipment is stored for long periods

  A common problem following the long term storage of any battery-operated equipment (or equipment using battery back-up for settings) involves discovering that the cells have leaked. Being an alkaline, battery fluid is highly corrosive and the damage that it can cause can be very difficult to repair, if repairable at all.

In terms of the maintenance of test and measurement devices, there are a few simple practises to follow:

- Generally speaking, digital instruments require much less maintenance compared to their analogue predecessors as they have far fewer mechanical/moving parts. That said, wear and tear, together with aging, can cause the accuracy of all test and measurement devices to deteriorate.

  In applications where the accuracy of test and measurement devices is crucial to the correct testing and repair of electronics equipment, a calibration schedule is required. In fact, this is often dictated by the requirements to meet a standard like ISO 9001:2015.

  It's unusual for small to medium enterprises to conduct their own check and calibration of test and measurement devices. It's more usual to return devices to the supplier for checking. In some cases, devices must be tested and calibrated by a dedicated NATA accredited calibration service (eg Smart Calibration P/L).

- Check for perished probe leads, cracks, exposed wire of any sort

  All plastic and rubber breaks down over time (and is said to "perish"). This can cause the insulation on probe leads to stiffen and crack which exposes the wire underneath. Another problem is the plastic insulation separates where it meets the probe or plug at each end, again exposing the wire underneath. An example is shown in Figure 9 below.

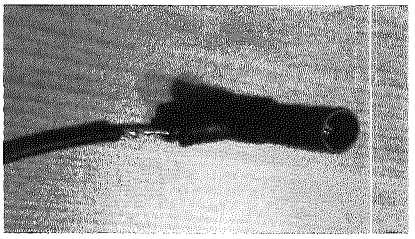

Figure 9

Having exposed wires on meter leads is obviously dangerous, particularly when measuring large voltages and currents. Check probe leads regularly and replace at the first sign of damage. Multimeter probe leads are pretty cheap so there's no excuse not doing so.

In terms of the care of test and measurement devices, there are a few simple practises to follow:

- Use the device correctly

  There are a few traps here. If a DMM can measure both potential differences and currents, (most can) there are usually separate sockets to for the red plug (ie one to use when measuring potential difference and one for measuring current). You must ensure the red plug is connected to the correct socket before attempting to make the measurement.

  Also, don't turn the function dial while you're making a measurement. And don't forget to turn the equipment off (and unplug it from the powerpoint) when attempting to make measurements of resistance between two points in the circuit while cold-testing.

- Use the device correctly, per the specified limits

  All test and measurement devices have maximum ratings for measuring potential difference and current that they can withstand without damage. You can find these figures in the device's specifications but they're also very often written on the device's faceplate. Avoid measuring voltages and currents that exceed these figures.

- Avoid placing devices on hot/cold surfaces and avoid hot items (like a soldering iron or heat gun) from accidentally coming into contact with the device.

- Avoid dropping test and measurement devices

  Portable test equipment is often designed to withstand drops. Rubberised protective cases are particularly good at preventing damage to the case, especially on the edges. However, there's a limit to how much shock any test and measuring device can withstand. Sometimes the drop doesn't damage the case but does cause hairline fractures of the circuit board inside that are difficult to see with the naked eye.

- Don't tamper with internal adjustments

  The design of test and measurement devices usually includes the use of precision components (that is, components with very low tolerance figures and tight specifications for other electrical properties). Despite that, there is often still a need to trim component values to obtain the exact amount needed for the circuit to operate optimally and with the required accuracy. To that end, trimpots, trimcaps and other adjustable components are used.

  It's important that you never adjust these components unless you know what you're doing or are being supervised by somebody who knows what they're doing. Once an adjustable component's setting has been changed, it can be very difficult to return it to the correct position. This can make it very expensive when a suitably trained person has to do that for you.

- Replace batteries every two years

  It's better to be safe than sorry. This could be extended to every five years if the batteries have an extra-long shelf life. (For example, there are Energizer batteries with a twenty year shelf life.)

- Don't cover ventilation holes

  All electronics equipment generates heat when operated. Where this involves a lot of heat, it's usual to provide ventilation which can be as simple as holes in the case or a fan to draw in cooler air and force out warmer air. Either way, it's important not to block the ventilation as this would cause the equipment to overheat.

  It's also worth checking ventilation holes periodically as dust and other particles in the air can block them. This is especially true where a fan is used to help with cooling.

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Transformer efficiency (losses) and turns ratio

When you learn about the principles of operation of linear DC power supplies for this unit (EC0075), you're expected to demonstrate evidence of your knowledge of:

- Transformer turns ratio and losses

You have learnt about transformers for another unit (EC0074) but the following notes have been provided here for your convenience.

Transformer efficiency

The type of transformer used in linear DC power supplies is the mains transformer. This is important to know because most commercially available mains transformers are so well designed they have very few losses giving a typical efficiency of 98%. In the context of an introductory unit on DC power supplies, its reasonable to round the efficiency figure up to 100% and this has implications for calculating a transformer's secondary voltage given its primary voltage and turns ratio.

Transformer turns ratio

Transformer turns ratio is a simple concept - It's the ratio of the number of primary turns to the number of secondary turns. It is calculated as shown below:

$$N = \frac{N_P}{N_S}$$

Where:
N_s is the number of turns in the secondary
N_p is the number of turns in the primary and
N is the turns ratio

The relationship between transformer primary and secondary voltages

When the efficiency of a transformer is 100% (which is the efficiency figure we use for mains transformers) the relationship between the transformer's primary (ie input) and secondary (ie output) voltages is simple. If there are the same number of turns in the primary and secondary windings, the primary and secondary voltages are the same giving a *one-to-one* transformer.

If there are fewer windings in the secondary than in the primary, the secondary voltage is proportionally smaller than the primary voltage giving a *step-down* transformer. If there are more windings in the secondary than in the primary, the secondary voltage is proportionally bigger than the primary voltage giving a *step-up* transformer.

Once the transformer's turns ratio is known, its secondary voltage can be found if the primary voltage is known, as shown below:

$$v_S = \frac{v_P}{N}$$

Where:
v_s is the secondary voltage
v_p is the primary voltage and
N is the turns ratio

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Student notes

Section 1 Diode junction characteristics; and diode opearation in simple DC circuits

Purpose To develop your ability to interpret manufacturer's data for diodes and to test a rectifier diode to determine whether or not it is faulty.

Objectives At the end of this section you should be able to:

- Draw the schematic symbol for a diode
- Name and identify the terminals of a diode
- Name the semiconductor materials commonly used for diodes
- Describe the operation of a diode over a range of anode-cathode voltages
- Define the terms *reverse bias* and *forward bias*
- Interpret the graph of anode-cathode voltage versus anode-cathode current of typical rectifier diodes
- Define the terms *reverse breakdown voltage*, *reverse leakage current*, *forward voltage*, *forward current* and *maximum forward current*
- Determine specified values of reverse breakdown voltage, reverse leakage current, forward voltage and maximum forward current of a diode from manufacturer's data
- Calculate the current and potential differences around a series circuit consisting of a battery, diode and resistor in which the diode is reverse and forward biased
- Conduct tests on diodes using a DMM to identify the anode and cathode terminals and determine whether or not the diodes are faulty
- Measure diode operating conditions in a simple DC circuit using a DMM

Introduction

This subject deals with the principles of operation of DC power supplies. [Note: Only simple *linear* power supplies are covered. More sophisticated linear power supplies and *switched-mode* power supplies are dealt with in another subject.] Section 2 of this workbook deals with the need for power supplies and what they do. Section 2 also discusses the operation of the power supply from a system perspective with the aid of a diagram called a *functional block diagram*. The remainder of this workbook deals with circuits that perform the tasks of these functional blocks which you'll be expected recognise and analyse.

This section lays the necessary foundation for all of your learning about power supplies by introducing you to the operation of the *diode*.

Diodes

Diodes are called *semiconductor* devices because they belong to a group of electronics components that are made from semiconductor materials such as germanium (whose chemical symbol is *Ge*) and, much more often, silicon (*Si*).

There are several different types of diodes including *rectifier* diodes, *small signal* diodes and *zener* diodes. They all operate in the same basic way, the differences between them are in their electrical specifications which affects the applications in which they can be used.

The schematic symbols used to represent rectifier (and small signal) diodes are shown in Figure 1 below.

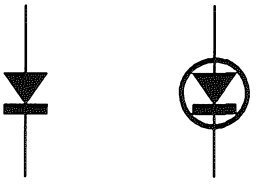


Figure 1 *Schematic symbols used to represent rectifier (and small signal) diodes*

Like the resistor, the diode has two leads (or *legs*). However, unlike resistors the diode is a polarised device: that is, to operate as expected, the diode can only go in the circuit one way. One of the diode's leads is positive (called the anode) and the other is negative (called the cathode). Which diode's leads are anode and cathode are shown on the schematic symbol in Figure 2 below.

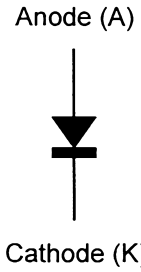


Figure 2 *The polarity of the diode's leads*

Working out which lead is which on an actual diode is fairly easy. Diodes usually have a band marked on the body towards one end. Rectifier diodes are usually black and the band is silver. The diode's cathode is the lead on the same end of the body as the band. This is shown in Figure 3.

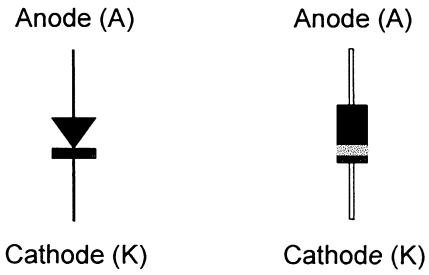


Figure 3 *The cathode is the lead on the same end of the body as the silver band*

The physical construction of diodes

The basic physical construction of a diode consists of two parts. The end that the diode's cathode is connected to is a semiconductor material that has an impurity added to make it *n-type*. The end that the diode's anode is connected to is the same semiconductor material but has a different impurity added to make it *p-type*. The point where the two types of semiconductors meet is called the *p-n junction*. The basic physical construction of a diode is shown in Figure 4 below.

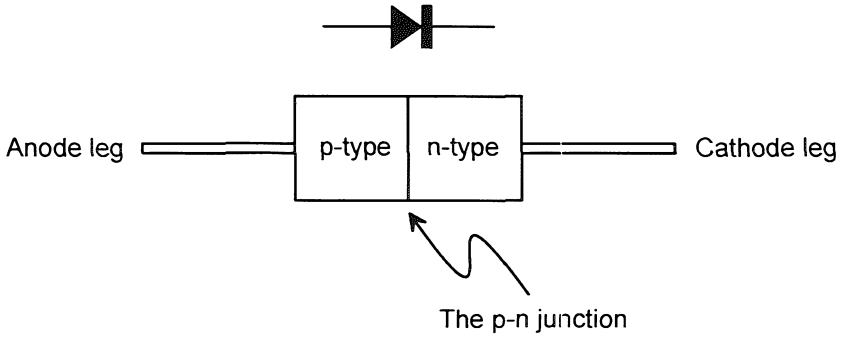


Figure 4 *The basic physical construction of a diode*

What do rectifier diodes do?

The diode's physical construction doesn't give us much of a clue about what the device does. Put simply, a diode is like a one-way valve for current. That is, current flows through them in one direction only: from anode to cathode. This is shown in Figure 5 below.

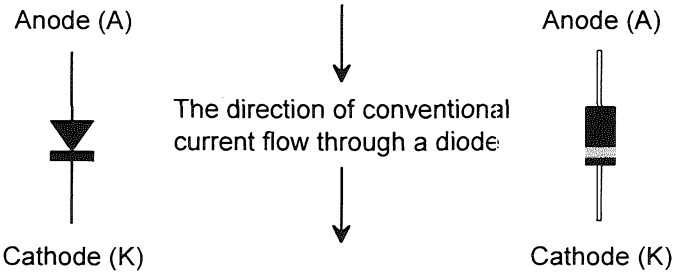


Figure 5 *The direction of conventional current through a rectifier diode*

Diode biasing

When a potential difference is developed across a diode it is said to be *biased.* As there are two polarities in which a potential difference across a diode can be developed, there are two modes of biasing. When the diode's anode is made negative with respect to its cathode it is said to be *reverse biased* (or *turned off*). A circuit that would reverse bias a diode is shown in Figure 6 below.

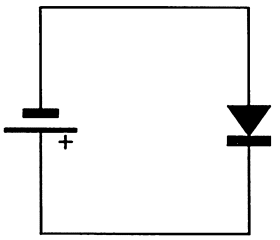


Figure 6 *When a diode's anode is made negative with respect to its cathode it is said to be reverse biased*

When biased in this way, the diode acts like an open-circuit and no current flows. Having said that, there two exceptions to this. First, a current actually does flow when the diode is reverse biased but it is tiny (in the order of μA) and is called *leakage current* (I_R). Leakage current is so small that it cannot be measured using conventional multimeters and it doesn't upset the operation of most circuits. So, leakage current can be ignored.

Second, the diode can be forced to conduct measurable amounts of current when it is reverse biased if the potential difference across it is big enough. When the diode conducts in the reverse direction it is said to *breakdown* and the p-n junction can be damaged. For rectifier diodes, the reverse bias voltage necessary for it to breakdown varies from one device to another but is almost always over 100V and typically more like 400V to 1kV.

As you will learn later in this subject, the voltage that can cause a diode to conduct when it is reverse biased is an important specification of diodes. As such it has a name and is called the *reverse breakdown voltage* (V_R).

When the diode's anode is made positive with respect to its cathode by 0.6V it is said to be *forward biased* (or *turned on*). A circuit that would forward bias a diode is shown in Figure 7 below.

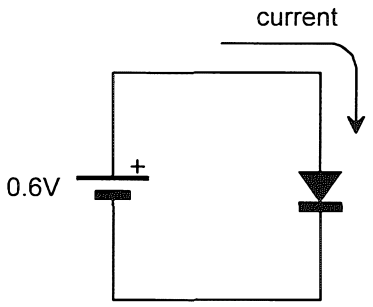


Figure 7 *When a diode's anode is made positive with respect to its cathode by 0.6V current flows and the diode is said to be forward biased*

When biased in this way, the diode acts like a near short-circuit and a current flows called the *forward current* (I_F).

There are two important points to make about the forward biasing of diodes. First, the potential difference across the diode that turns it on is called the *forward bias voltage* (V_F) and it varies from device to device. Having said that, the forward bias voltages only varies over a range between 0.5V and 0.7V. So, for convenience, 0.6V is used for all rectifier diodes.

Second, current doesn't flow in the circuit if the potential difference across the diode is less than the forward bias voltage. This is shown in Figure 8 below.

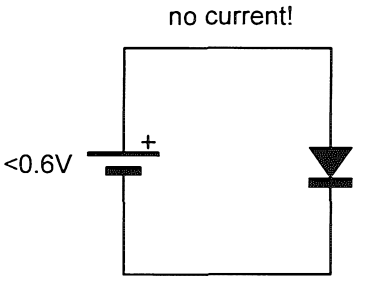


Figure 8 *Current will not flow in this circuit even if the diodes anode is made positive with respect to its cathode if the potential difference across the diode is less than its forward voltage drop (which is typically 0.6V)*

The diode's operation can be described using a graph of anode-cathode voltage versus anode-cathode current. The graph is shown in Figure 9 below.

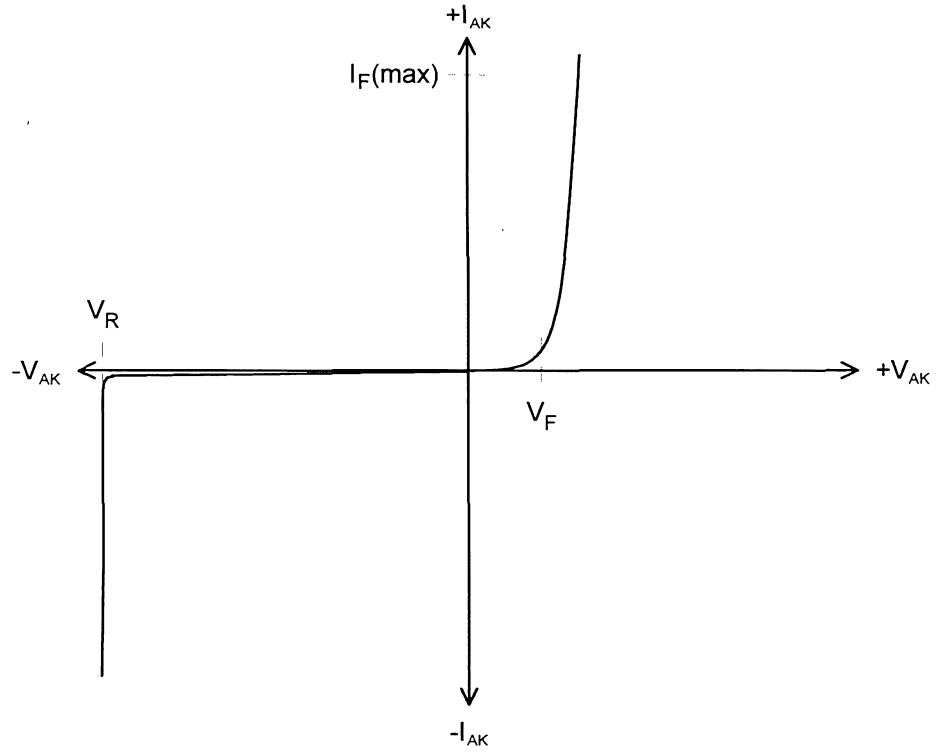


Figure 9 *The graph of anode-cathode voltage versus anode-cathode current*

Graphs like this one are used to explain the operation of lots of components (and circuits) in electronics. But, as it takes a lot of practice to be able to interpret these kinds of graphs, the following notes provide a detailed interpretation of this one to help you.

Let's analyse the upper right-hand side of the graph in Figure 9 first. This quadrant graphically shows what happens to the diode when its anode is made positive with respect to its cathode as shown in Figure 10 below.

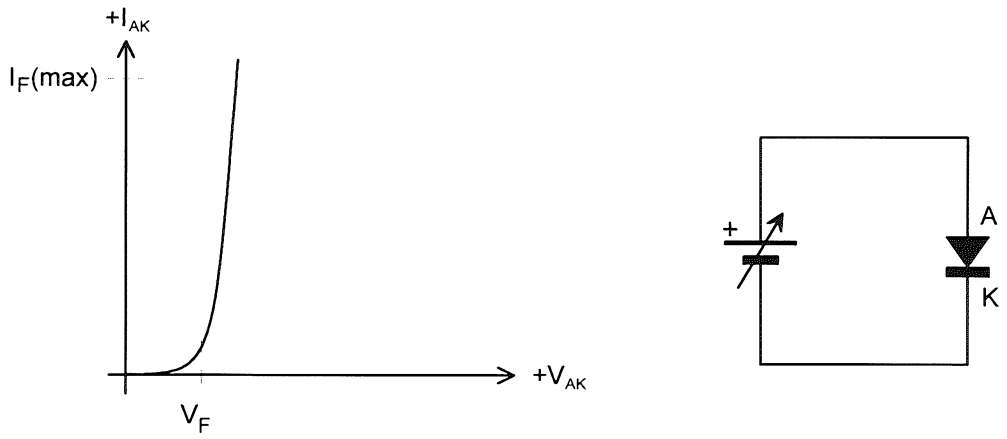


Figure 10 *The upper right-hand side of the graph represents what happens to the diode when its anode is made positive with respect to its cathode as it is in the circuit above*

The bottom left corner of this graph shows that when the diode's anode is made positive with respect to its cathode but is a voltage below the diode's forward bias voltage (V_F), no current (or a only a negligible amount of current) flows. This aspect of diode operation is highlighted in Figure 11 below.

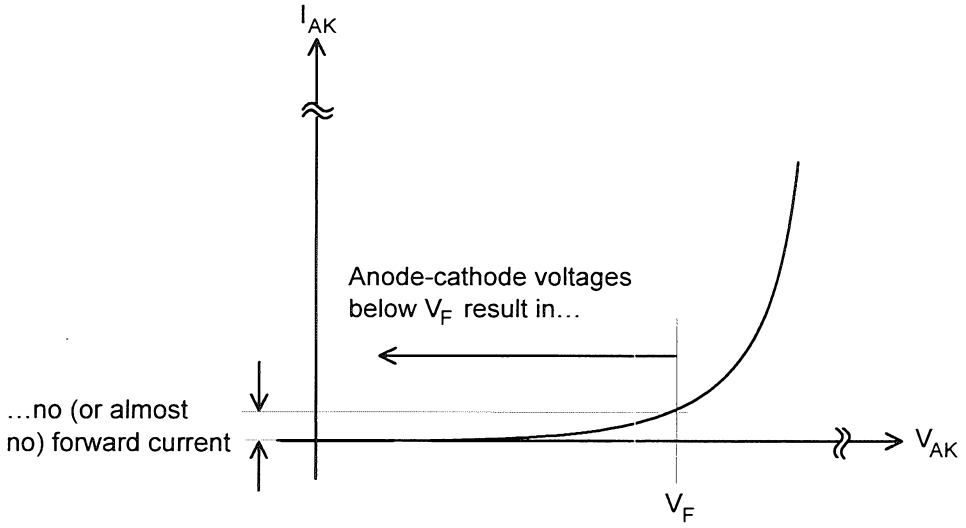


Figure 11 *If the potential difference across diode is less than the diode's forward bias voltage then there is no (or almost no) forward current*

Once the anode-cathode voltages exceeds 0.6V the diode turns on and a measurable amount of current flows from the anode to the cathode. This aspect of diode operation is highlighted in Figure 12 below.

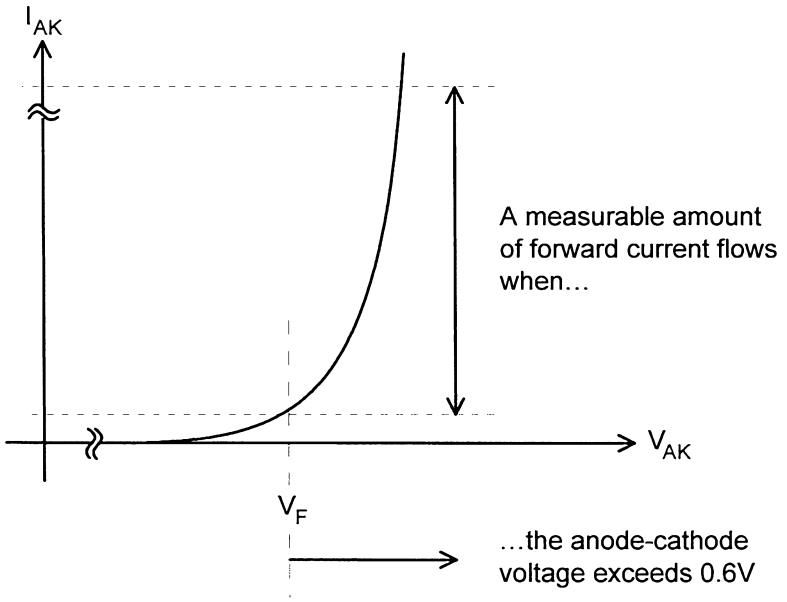


Figure 12 *A measurable amount of forward current flows when the anode-cathode voltage exceeds the diode's forward bias voltage (which is typically 0.6V)*

The manufacturers of diodes always specify a maximum allowable forward current denoted by $I_F(max)$. If this current is exceeded, the device will overheat and be destroyed. Figure 13 below shows where the maximum forward current occurs on the graph of anode-cathode voltage versus anode-cathode current.

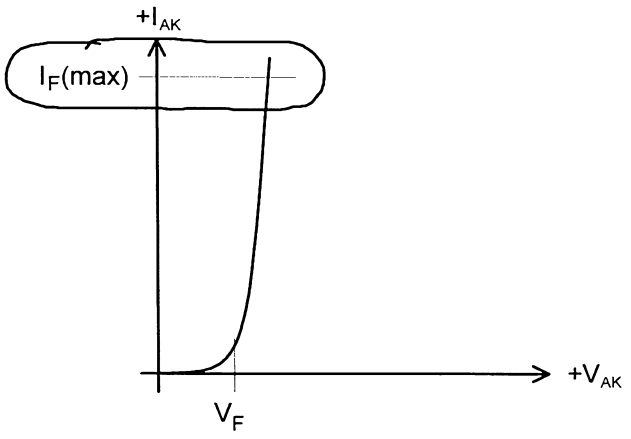


Figure 13 *The maximum forward current specified by the manufacturer*

The graph also shows that, as the forward current through the diode increases, the potential difference across the diode also increases. However, the potential difference across a diode doesn't change very much despite relatively large changes in forward current. Importantly, this means that Ohm's Law is not at work here - for example, a doubling of the forward current will not result in a doubling of the potential difference across the diode. This relationship between forward current and the potential difference across the diode is highlighted in Figure 15 below.

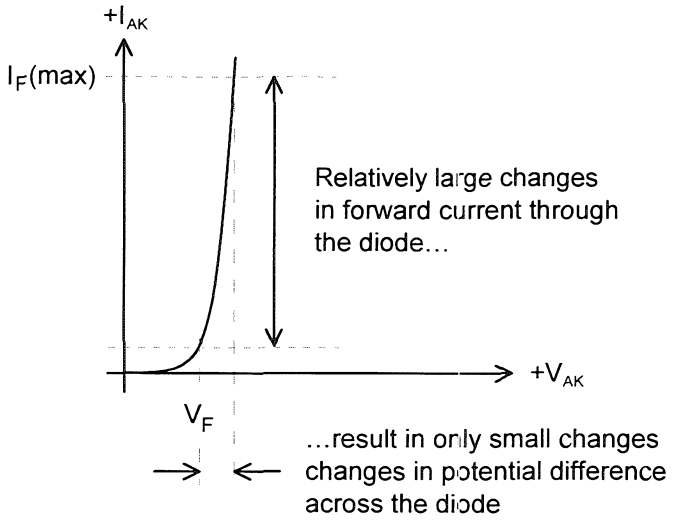

+I_AK
I_F(max)
Relatively large changes in forward current through the diode...
+V_AK
V_F
...result in only small changes in potential difference across the diode

Figure 15 *The potential difference across a forward biased diode doesn't change very much despite large changes in forward current*

The typical potential difference across a rectifier diode when it has the maximum rated forward current flowing through it ($I_F(max)$) is about 1V. However, the increase is so small relative to other voltages in circuit in which diodes are used that the increase is not worth worrying about. As such, the notes in this workbook standardise on 0.6V for the potential difference across a forward biased diode regardless of the size of the forward current.

Now let's analyse the lower left-hand side of the graph in Figure 9 (on page 1-7). This quadrant graphically shows what happens to the diode when its anode is made negative with respect to its cathode as shown in Figure 16 below.

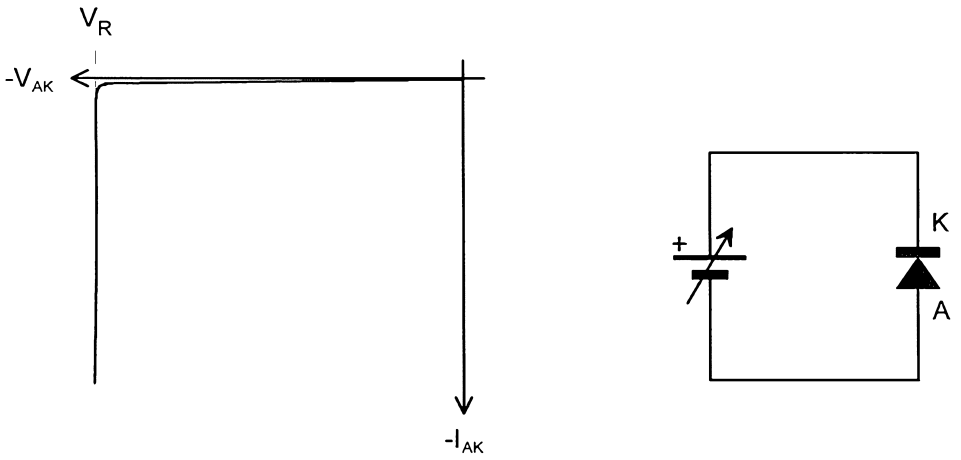


Figure 16 *The lower left-hand side of the graph represents what happens to the diode in the circuit shown*

The top of the graph in Figure 16 above shows that when the diode's anode is made negative with respect to its cathode and the potential difference across the diode is below the diode's rated reverse breakdown voltage (V_R), only a minute amount of current flows (leakage current). This aspect of diode operation is highlighted in Figure 17 below.

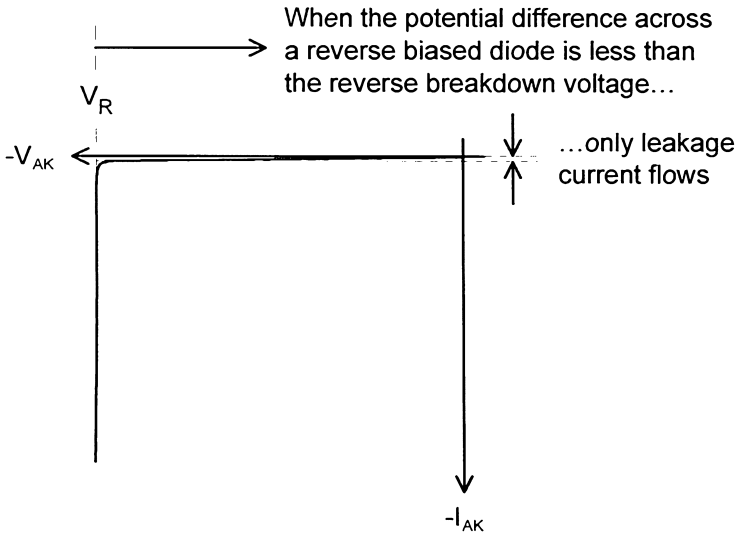

When the potential difference across a reverse biased diode is less than the reverse breakdown voltage...
V_R
$-V_{AK}$
...only leakage current flows
$-I_{AK}$

Figure 17 *Only leakage flows through a reverse biased diode if the potential difference across it is less than the diode's rated reverse breakdown voltage*

However, the graph also shows that once the potential difference across a reverse biased diode exceeds the diode's rated reverse breakdown voltage current will flow through it. Importantly, current will flow from cathode to anode which is the "wrong" way through it.

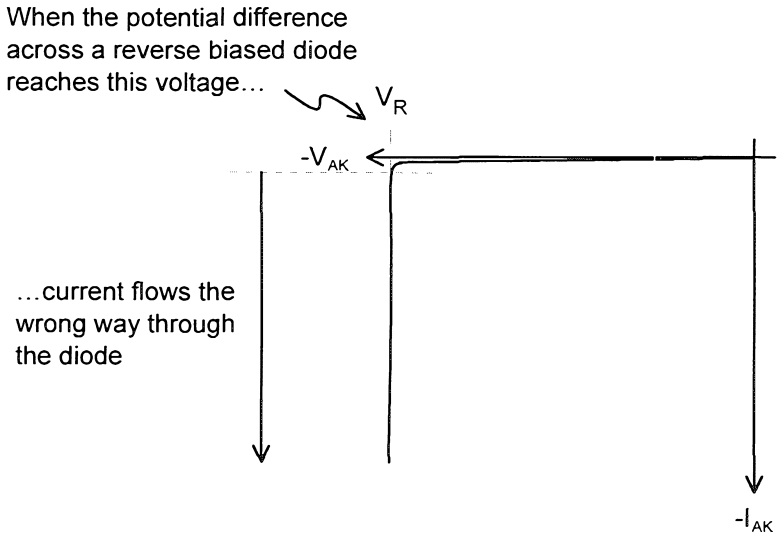

When the potential difference across a reverse biased diode reaches this voltage...
V_R
$-V_{AK}$
...current flows the wrong way through the diode
$-I_{AK}$

Figure 18 *A measurable amount of current flows when the reverse bias voltage exceeds the reverse breakdown voltage*

Schottky diodes

Schottky diodes operate almost exactly per the description of regular silicon diodes on the preceeding pages. The key difference between schottky diodes and regular silicon is a lower forward voltage drop - It's about 0.3V compared to about 0.6V for regular silicon diodes. This can be very useful in lots of applications as you will learn.

Diode operation in a simple circuit

The diode biasing circuits used so far have been simplified for the purposes of explanation. In fact, the circuits are oversimplified and, if wired, excessive currents would flow in the circuits and damage the diode.

So now let's consider what happens in a more realistic diode circuit. Figure 19 below shows a simple series circuit consisting of an EMF, a resistor and a rectifier diode.

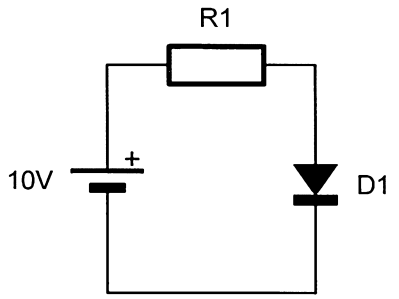


Figure 19 *A simple series circuit consisting of an EMF, a resistor and a diode*

In this circuit, the diode's anode is connected to the EMF's positive terminal (via *R1*) and the diode's cathode is connected to the EMF's negative terminal. As such, when the EMF is greater than 0.6V the diode is forward biased and current flows.

In the circuit in Figure 19, the EMF voltage is 10V so current flows in the circuit as shown in Figure 20 below.

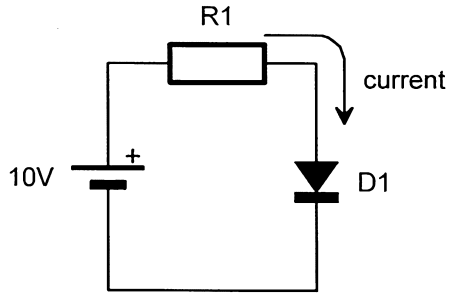


Figure 20 *When the diode is connected in this way, when the EMF is greater than 0.6V, current flows*

As you know, the potential difference across a forward biased diode is typically 0.6V and this is be true for the diode in the circuit of Figure 20 (on the previous page). Importantly, you'll recall that Kirchhoff's Voltage Law states that the sum of the potential differences in a series circuit always equal the EMF voltage. That being the case, with an EMF of 10V and a diode forward voltage drop of 0.6V, the potential difference across the resistor in Figure 20 must be 9.4V. These voltages are shown in Figure 21 below.

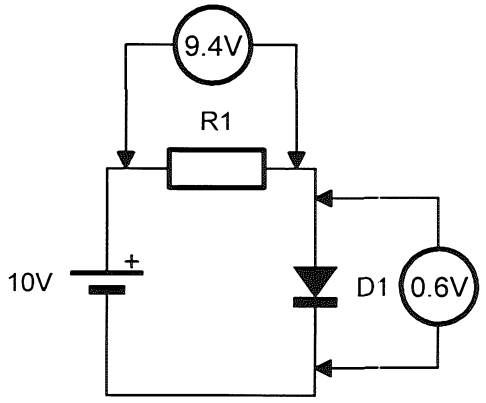


Figure 21 *The potential differences around the circuit of Figure 20*

From this analysis it can bee seen that the potential difference across the resistor is always equal to the EMF voltage minus the forward voltage drop across the diode. As an equation, this can be written as:

$$V_{R1} = E - 0.6V$$

Once the potential difference across the resistor is known, Ohm's Law can be used to find the circuit current. The equation looks like:

$$I = \frac{V_{R1}}{R1}$$

Practise calculating voltages and currents around a series circuit consisting of an EMF, resistor and a diode by trying the following questions.

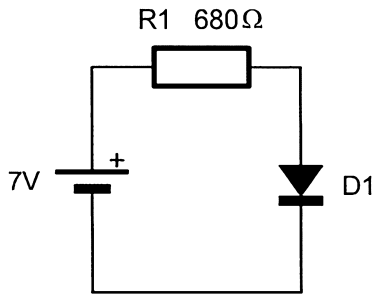


Figure 22

1. What is the potential difference across the diode *D1*?

   0.6 V

2. Calculate the potential difference across the resistor *R1*.

   7 − 0.6 = 6.4 V

3. Calculate the current through the diode *D1*.

   $I = \frac{V_R}{R_1} = \frac{6.4}{680} = 9.41\,mA$

4. Calculate the power dissipated by the diode.

   $P_D = V_D \times I = 0.6 \times 0.0094 = 5.7\,mW$

As you will learn, there are circuits in which diode are reverse biased for short periods of time. So, let's analyse what happens in the simple circuit of Figure 20 if the diode is turned around. First, the circuit looks like the circuit in Figure 23 below.

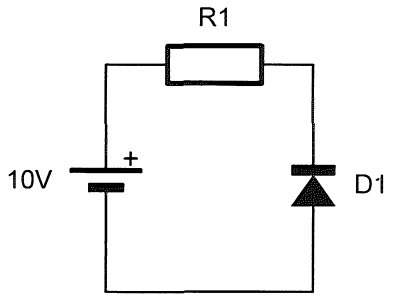


Figure 23 *The circuit in Figure 19 with the diode turned around*

In this circuit, the diode's anode is connected to the EMF's negative terminal and the diode's cathode is connected to the EMF's positive terminal. As such, when the EMF is less than the diode's reverse breakdown voltage (which it should be), no current flows in the circuit (other than a minute amount of leakage current which can be ignored).

As you know, if the current through a resistor is 0A, then the potential difference across it must be 0V. And, as Kirchhoff's Voltage Law states that the sum of the potential differences in a series circuit always equal the EMF voltage, the reverse bias voltage across the diode must be equal to the EMF (which is 10V in this case). These voltages are shown in Figure 24 below.

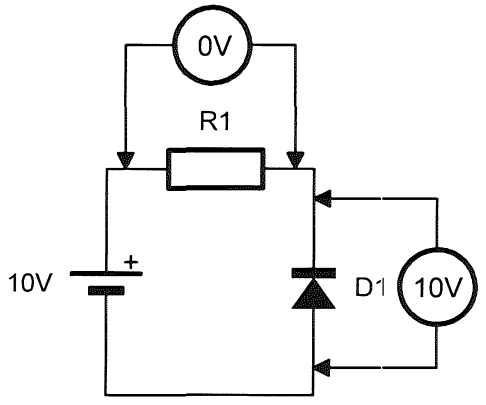


Figure 24 *The potential differences around the circuit of Figure 23*

Testing rectifier diodes

At some stage in your work as a repair technician you'll suspect a rectifier diode of being faulty. To confirm your suspicion you'll need to remove the diode from the circuit and test it. Testing diodes for faults basically involves testing the p-n junction. This can be done using either an analog multimeter (AMM) or a digital multimeter (DMM).

When using an AMM, test the diode using the AMM's ohmmeter with the range control set to the ×100 range (or nearest equivalent). Connect the meter's probes to the diode's leads and measure the resistance. Then, reverse the meter's probes and measure the resistance again. If one of the measurements is very high and the other is very low then the diode is probably functional.

The diode test procedure when using DMMs is identical to the procedure just described. However, there is a little difference. The ohmmeter function on most DMMs can't provide enough current to forward bias a p-n junction. So, manufacturers of DMMs usually provide a special diode test facility (often denoted by a little schematic symbol for a diode).

The diode test facility works in the following way. Inside the DMM is a constant current source, the positive side of which is connected to the meter's red probe and the negative side is connected to the black probe (assuming the leads have been plugged into the meter correctly). When the meter is connected across the diode, the current source inside tries to pump current through the diode and at the same time measure the potential difference across it. The equivalent circuit of this is shown in Figure 25 below.

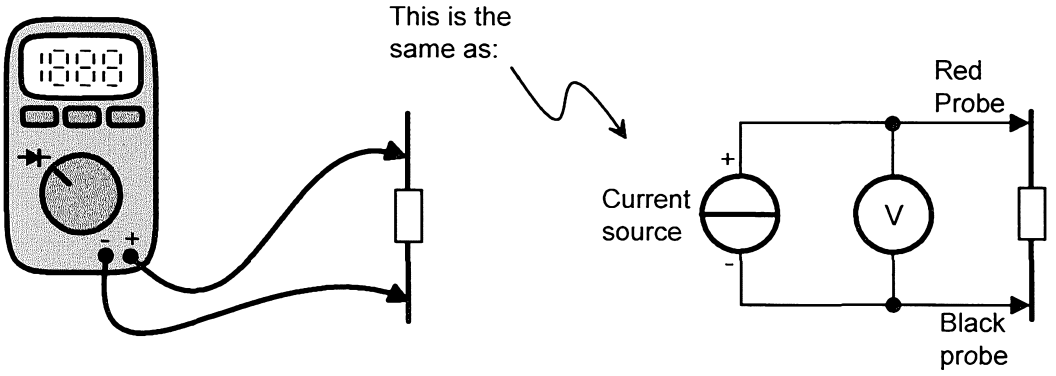
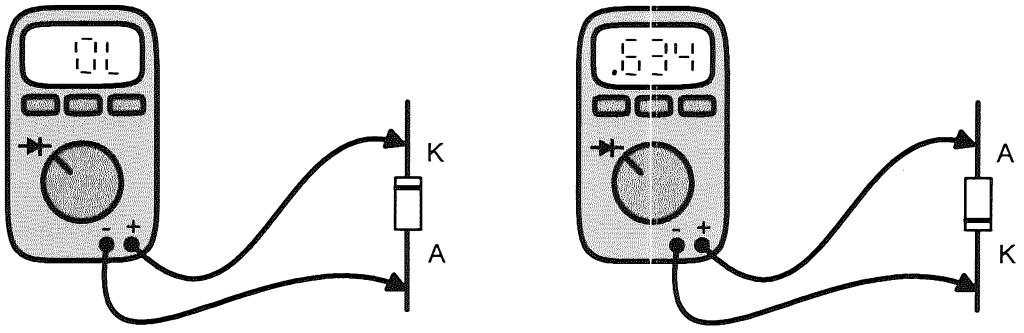


Figure 25 *The equivalent circuit of connecting a DMM across a diode when the DMM is set to the diode test mode*

When used to test a functional diode, the diode test mode will show one of two voltages:

- If connecting the DMM reverse biases the diode then the meter will display a voltage that is the same as the voltage when the meter leads are not connected to anything ("OL" on most of the meters at this college).
- If connecting the DMM forward biases the diode then the meter will display the diode's forward voltage drop (which can be anything from 0.5V to 0.75V).

These measurements are shown in Figure 26 below.



Diode reverse biased by the DMM Diode forward biased by the DMM

Figure 26 *The meter readings when the meter reverse biases and forward biases a functional diode*

There are two main faults that diodes experience and this test procedure identifies both of them. A diode can either go open-circuit between the anode and the cathode (so it becomes a no-way valve instead of a one-way valve!). Or, a diode can go short-circuit between the anode and the cathode (so it becomes a two-way valve which is not really a valve at all).

If a diode is open-circuit anode-cathode, the meter will give a reading that is the same as when the probes are not connected to anything and will do so regardless of the polarity of the probe connections (see Figure 27).

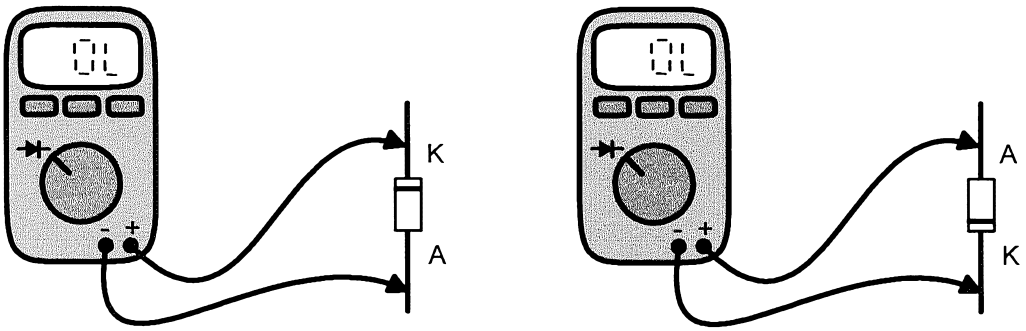


Figure 27 *The meter readings for both connections when the diode is open-circuit*

If a diode is short-circuit anode-cathode the meter will give a reading of zero (the same as if the probes are shorted together) regardless of the polarity of the probe connections (see Figure 28).

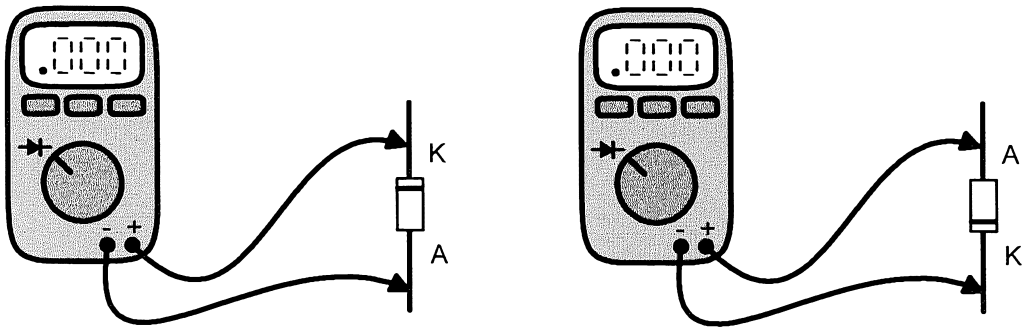


Figure 28 *The meter readings for both connections when the diode is short-circuit*

Identifying a diode's leads

Although you can usually work out which diode lead is the cathode by inspection, sometimes this isn't possible. The band might look more like it's in the middle rather than to one end or the band may not even have been put on.

This isn't really a problem once you know how to test diodes because it is possible to work out which lead is the anode and which lead is the cathode by measurement. Assuming the diode is functional, connect the DMM in diode test mode to the diode in either polarity until you get a reading other than "OL" and "0.00". An example is shown using a DMM in Figure 29 below but the value could be anywhere between 0.15 and 0.75.

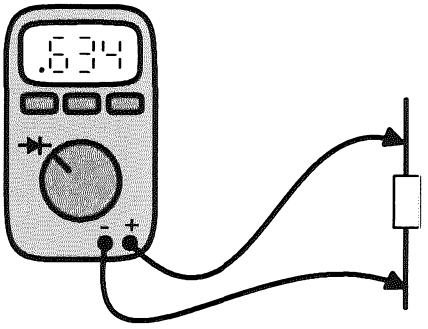


Figure 29 *Connect the meter leads to the diode until you get a "low" reading*

Once done, the red probe is connected to the diode's anode and the black probe is connected to the diode's cathode.

Student notes

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Skill practice 1

Practise testing rectifier diodes using a DMM and measuring diode operating conditions in a simple DC circuit

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1 hour to complete this exercise.

Equipment

- prototyping panel digital
- two DMMs
- 1N4007 diode
- BZW03C91 diode
- 1N5235 diode
- 1N5819 diode (schottky)
- 470Ω ¼W resistor banana
- leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Take one of the silicon diodes and write its number in the first column of one of the rows in Table 1 below.

4. Draw a little sketch of the diode in the next column and indicate on your drawing which lead you think is the anode (A) and which is the cathode (K).

5. Set the DMM to the diode test mode (denoted by a little diode symbol).

6. Connect the DMM's positive probe to the diode's anode and the negative probe to the diode's cathode.

7. Measure and record the diode's forward voltage drop.

8. Swap the meter leads so that the positive is connected to the diode's cathode and the negative is connected to the anode.

9. Observe and record the meter's reading.

10. Repeat Steps 3 to 9 for the remaining diodes.

Table 1

Diode's part number	Drawing of diode	Forward volt. drop	Reverse reading

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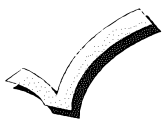
Question 1
What is the rule for determining which lead of a diode is the anode and which is the cathode using the diode test on a DMM?

Question 2
Is the forward voltage drop of silicon diodes exactly 0.6V? Explain your answer.

Question 3
Based on your measurements in Table 1, what is the difference between regular silicon diodes and schottky diodes?

Question 4
What is the problem with a diode that reads "OL" either way you connect the DMM's leads to the diode's terminals?

Question 5
What is the problem with a diode that reads "0.00" either way you connect the DMM's leads to the diode's terminals?



The teacher needs to check your work at this point...

11. Set the bench-mounted DC power supply to 10V then turn it off.

12. Wire the circuit of Figure 1 on the breadboard.

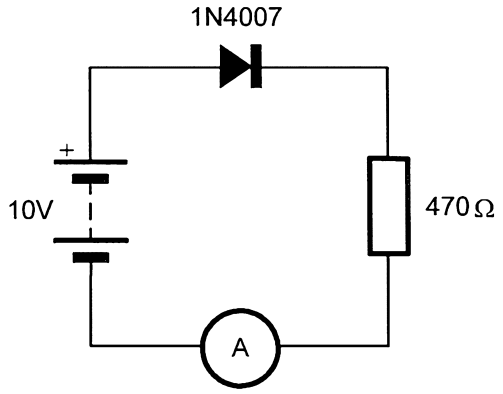


Figure 1

13. Set the DMM to the mA range then turn on the power supply. [Note: make sure that you've connected the leads to the DMM for measuring current not voltage.]

14. Measure the circuit current and the potential difference across the resistor and diode. Record your measurements in Table 2 below.

Table 2

Circuit current	
Potential difference across the resistor	
Potential difference across the diode	

Question 6
Why is the potential difference across the resistor the value that you measured and not 10V?

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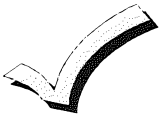
Question 7
Calculate the theoretical circuit current (which is the current through the diode) using Ohm's Law and your measured value of potential difference across the resistor.

Question 8
Are your measured ant theoretical currents the same? What might explain small differences between them?



The teacher needs to check your work at this point...

15. Switch off the DC power supply.

16. Reverse the polarity of the diode and switch the power supply back on.

17. Measure the circuit current and the potential difference across the resistor and diode. Record your measurements in Table 3 below.

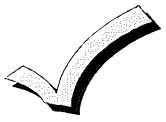
Table 3

Circuit current	
Potential difference across the resistor	
Potential difference across the diode	

Question 8
Why is the circuit current zero?

Question 9
Why is the potential difference across the resistor zero?

Question 10
Why is the potential difference across the diode 10V?



The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt form this chapter. Doing this will also help to prepare you for the tests.

1. Draw the schematic symbol of a diode.

2. Label the diode's terminals on your drawing above.

3. Which semiconductor material is most commonly used for diodes?

   ☐ Germanium
   ☐ Silicon

4. Diodes are made from

   ☐ A single layer of N-type semiconductor material only.
   ☐ A sandwich of N-type material between two layers of P-type semiconductor material.
   ☐ A single layer of P-type semiconductor material only.
   ☐ A layer of N-type and P-type semiconductor materials connected to each other.

5. Which layer of semiconductor material is the anode of a diode connected to?

   _____

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6. The diode in Figure 1 is

- ☐ reverse biased.
- ☐ forward biased.
- ☐ neither forward or reverse biased.

Figure 1

7. Ideally, how much current should flow through the diode when it is reverse biased?

- ☐ None
- ☐ An amount of current determined by Ohm's Law.
- ☐ Infinity

8. In practise, how much current flows through the diode when it is reverse biased?

_____

9. What is the name for this current?

_____

10. The diode in Figure 2 is

- ☐ reverse biased.
- ☐ forward biased.
- ☐ neither forward or reverse biased.

Figure 2

11. The diode in Figure 3 is

- ☐ reverse biased.
- ☐ forward biased.
- ☐ neither forward or reverse biased.

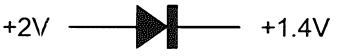

Figure 3

12. Show on Figure 4 below which way (conventional) current would flow when the diode is forward biased.

Figure 4

Questions 13 to 17 refer to the graph in Figure 5

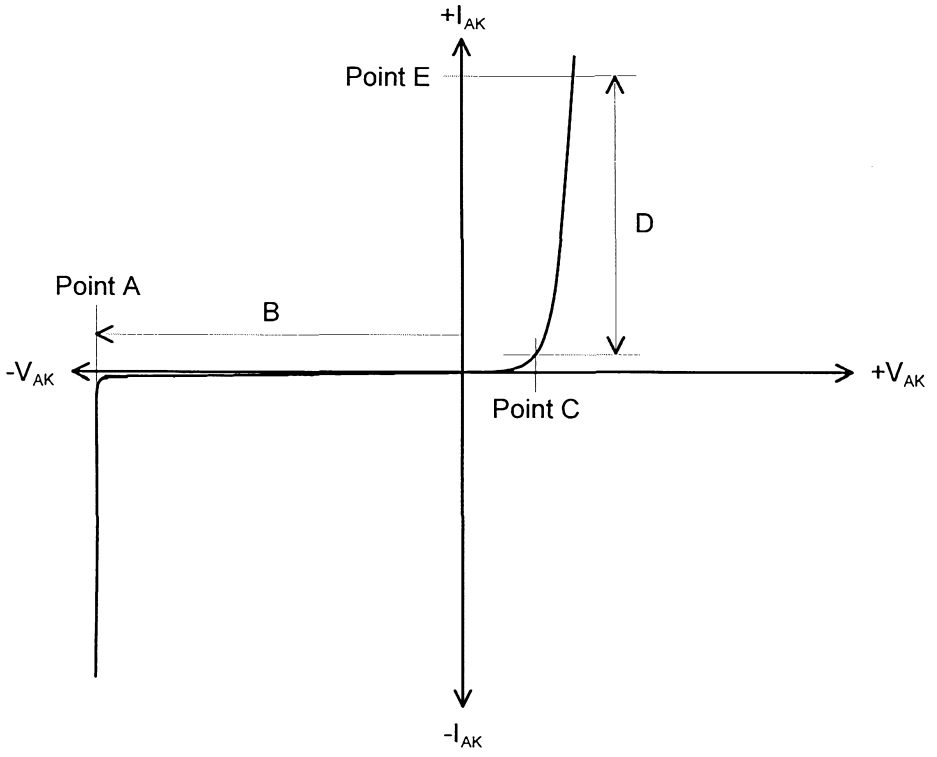

Figure 5

13. What is the name of the diode's characteristic on the graph at Point A?

- ☐ Forward bias voltage
- ☐ Reverse leakage current
- ☐ Maximum forward current
- ☐ Reverse breakdown voltage

14. What is the diode doing at voltages in the region on the graph marked "B"?

- ☐ Not conducting current
- ☐ Conducting leakage current
- ☐ Conducting forward current

15. What is the name of the diode's characteristic on the graph at Point "C"?

- ☐ Forward bias voltage
- ☐ Reverse leakage current
- ☐ Maximum forward current
- ☐ Reverse breakdown voltage

16. What is the diode doing at voltages in the region on the graph marked "D"?

- ☐ Not conducting current
- ☐ Conducting leakage current
- ☐ Conducting forward current

17. What is the name of the diode's characteristic on the graph at Point "E"?

- ☐ Forward bias voltage
- ☐ Reverse leakage current
- ☐ Maximum forward current
- ☐ Reverse breakdown voltage

18. Give values for the following characteristics of a 1N4006 using the data sheet given to you in the lesson:

(a) reverse breakdown voltage: _____

(b) reverse leakage current: _____

(c) maximum forward current: _____

(d) forward voltage: _____

Questions 19 to 21 refer to the circuit in Figure 6

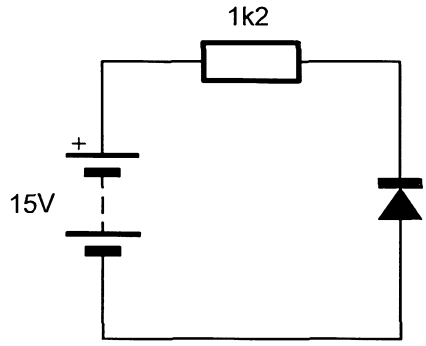

Figure 6

19. What is the potential difference across the diode?

20. What is the potential difference across the resistor?

21. What is the circuit current?

Questions 22 to 26 refer to the circuit in Figure 7

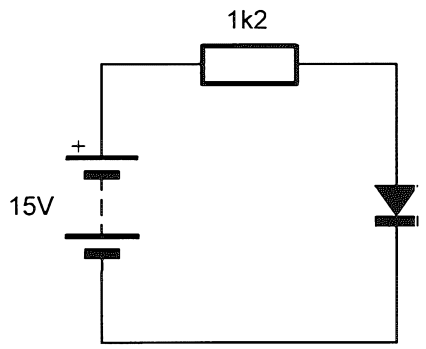

Figure 7

22. What is the potential difference across the diode?

23. Calculate the potential difference across the resistor.

24. Calculate the circuit current.

25. Calculate the power dissipated by the resistor.

26. Calculate the power dissipated by the diode.

Questions 27 to 29 refer to the circuit in Figure 8

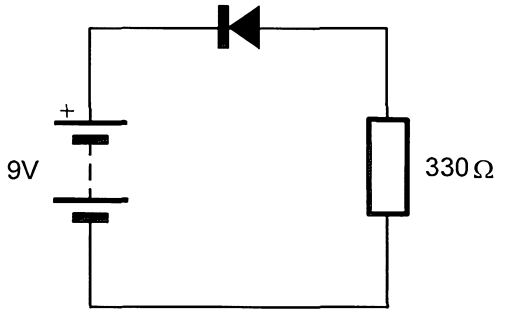

Figure 8

27. What is the potential difference across the diode?

28. What is the potential difference across the resistor?

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29. What is the circuit current?

Questions 30 to 33 refer to the circuit in Figure 9

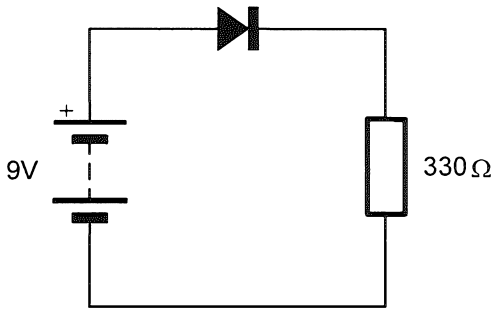

Figure 9

30. What is the potential difference across the diode?

31. Calculate the potential difference across the resistor.

32. Calculate the circuit current.

33. Calculate the power dissipated by the resistor.

Questions 34 to 36 refer to the diagram in Figure 10

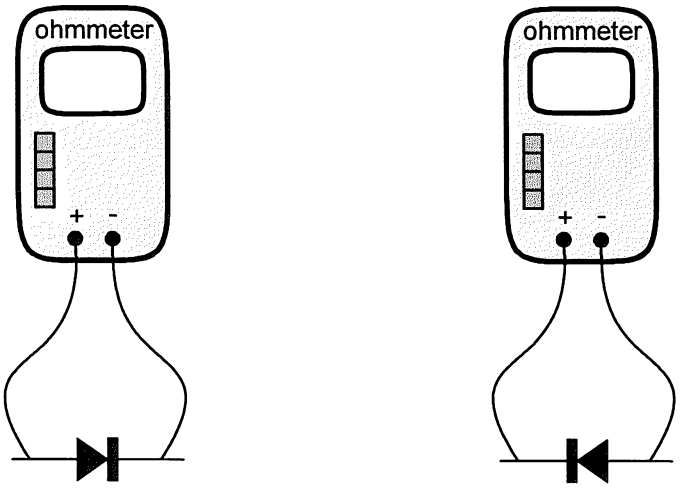

Figure 10

34. For the tests shown, which of the following set of ohmmeter readings indicate that the diode is **not** faulty?

- ☐ High resistance for both tests
- ☐ Low resistance for test 1 and high resistance for test 2
- ☐ Low resistance for both tests
- ☐ High resistance for test 1 and low resistance for test 2

35. What is the fault with the diode if the meter reads high resistance for both tests?

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36. What is the fault with the diode if the meter reads very low resistance for both tests?

Section 2 Power supply operating principles & applications; and half-wave rectification

Purpose To develop your ability to use test equipment to test half-wave rectifier circuits, recognise when the circuit is faulty, and identify the likely faulty component.

Objectives At the end of this section you should be able to:

- Explain the need for a power supply in electronics equipment
- Draw the generic functional block diagram of a power supply
- Explain the purpose of each block in the generic block diagram of a power supply
- Draw the circuit of a half-wave rectifier to produce a positive or negative output voltage
- Draw the potential difference and current waveforms for the load of a half-wave rectifier
- State the frequency of the potential difference and current waveforms for the load of a half-wave rectifier
- Calculate the maximum values of potential difference and current for the load of a half-wave rectifier given the transformer's primary voltage and turns ratio
- Calculate the average potential difference and current for the load of a half-wave rectifier given maximum values for each
- Draw the waveform of the potential difference across the diode in a half-wave rectifier
- Define the term *peak inverse voltage*
- Calculate the peak inverse voltage of a half-wave rectifier circuit given the transformer's primary voltage and turns ratio
- Choose diodes with suitable specifications for the reverse breakdown voltage and forward current for half-wave rectifier circuits
- State an advantage and a disadvantage of the half-wave rectifier
- Use an AMM and an oscilloscope to perform measurements of rectifier diode operating conditions in half-wave rectifier circuits

Introduction

The last section introduced you to the basic construction and operation of rectifier diodes. This is an important first step to learning about DC power supplies because they all use rectifier diodes. This section explains the need for DC power supplies and the basic principles of their operation. You'll also be introduced to the half-wave rectifier circuit.

The need for DC power supplies

As you know, the supply of electricity to offices, factories and homes in Australia is based on an AC power distribution system. AC is preferred to DC because, using a transformer, the AC voltages generated by power stations can be easily stepped-up to extremely large voltages (as high as 660kV in some cases). Importantly, in stepping the voltages up, the currents in the transmission lines are stepped-down which reduces cable losses.

However, all electronic equipment requires DC voltages to operate not AC. Moreover, the more stable the DC voltage, the better most electronics equipment usually work. That being the case, all mains operated electronics equipment must convert the AC mains into the very stable DC needed by the circuits inside. This is the job of a DC power supply.

There is a DC power supply inside all mains operated electronics equipment and, because of their connection to mains, faults in this part of the circuitry are common. That being the case, it is essential for the repair technician to have a good understanding of how DC power supplies operate.

The generic functional block diagram of a (linear) DC power supply

As mentioned above, all mains operated electronics equipment have a DC power supply inside. However, power supply circuits vary from one piece of equipment to another. To help you understand the general principles of operation that underpin all of these circuits, it is useful to learn about the operation of DC power supplies at the functional block level.

Figure 1 below shows the block diagram of a DC power supply. All (linear) DC power supplies consist of these functional blocks.

THIS WILL BE IN EXAM

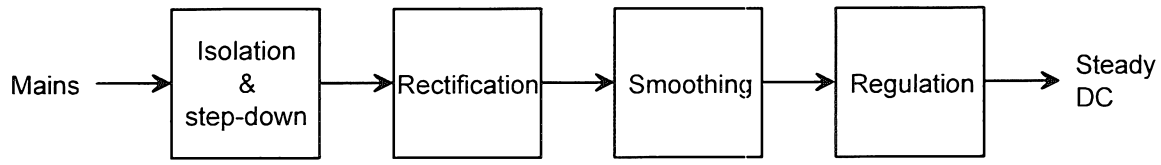

Figure 1 *The generic block diagram of a DC power supply*

A discussion of the function of each block in the diagram follows.

Isolation and step-down

As DC power supplies connect to mains it is essential that some method of electrical isolation be provided so that there is no direct electrical connection from any of the circuitry inside the equipment to mains. This ensures that, in the event of a component failure, it is impossible for mains voltages to reach any part of the equipment that should have no voltage or only low voltages present. This is done to prevent the users and technicians from coming into direct contact with mains which can be fatal.

In addition to this, the mains voltage needs to be efficiently stepped-down from a high voltage (usually 240V for domestic supplies and 415V for industrial supplies) to the much smaller voltages required by most electronics equipment.

The mains transformer is the perfect device to fulfil both of these functions. Recall that there is no electrical connection between the primary and secondary windings of a transformer so it provides the necessary electrical isolation from mains. Transformers can also step voltages down by having fewer windings in the secondary than in the primary. At the same time, their efficiency can approach 100% so there are relatively few losses.

The output of the isolation and step-down functional block in a power supply is an AC voltage that is smaller than the mains (see Figure 2 below).

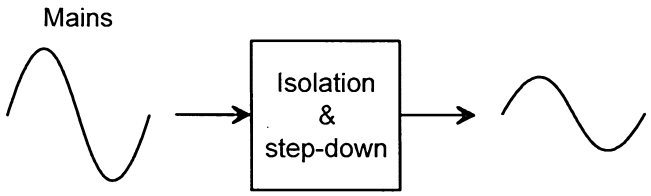

Figure 2 *The typical input and output of the isolation and step-down block*

Rectification

The purpose of rectification is to convert the voltage out of the transformer from one that alternates polarity (AC) to a voltage that doesn't (DC). Unfortunately, rectification can't stop the magnitude of the voltage from changing so the rectification circuit produces a pulsating DC.

There are actually two types of pulsating DC that can be produced and both are shown in Figure 3 below.

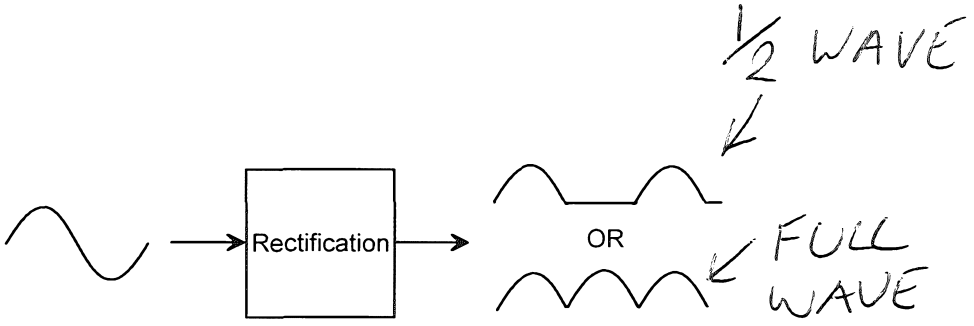

Figure 3 *The typical input and both types of output of the rectification block*

Smoothing (or filtering)

The purpose of the smoothing circuit is to smooth out the humps in the pulsating DC from the rectification circuit (see Figure 4 below).

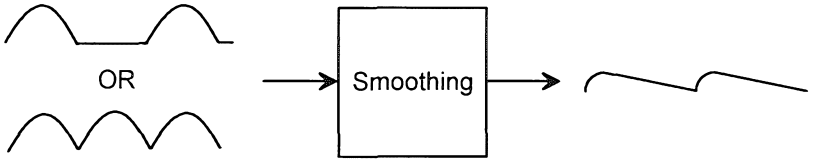

Figure 4 *The typical input and output of the smoothing block*

Regulation

The purpose of regulation is to make the power supply's output voltage as constant as possible for changes in mains voltages and load current. This usually has the added benefit of making the power supply's DC output voltage even more smooth (see Figure 5).

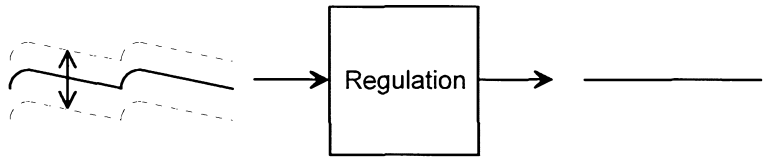

Figure 5 *The typical input and output of the regulation block*

In summary, the outputs of each block are shown in Figure 6 below.

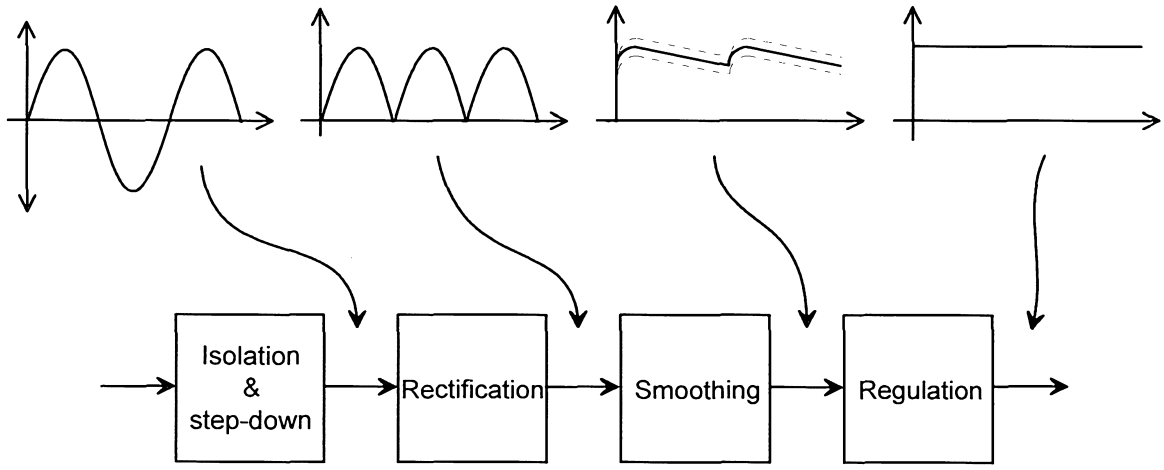

Figure 6 *The typical input and output of each functional block of a DC power supply (though only one of the two types of output from the rectifier is shown)*

The remainder of this subject examines the operation of simple but effective circuits that perform the rectification, smoothing and regulation functions of DC power supplies. There's no need to look at the first functional block because you have already learnt about transformers in an earlier subject.

There are three different circuits that can be used to perform rectification. These are:

- the half-wave rectifier
- the centre-tapped transformer full-wave rectifier
- the bridge rectifier

This section introduces you to the first of these.

Half-wave rectification

Figure 7 below shows the circuit of a half-wave rectifier connected across the output of a mains transformer. As you can see, the half-wave rectifier circuit consists of a single diode.

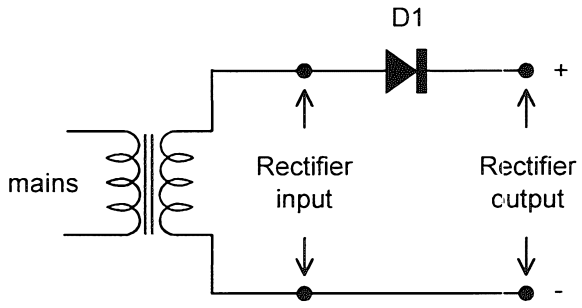

Figure 7 *Half-wave rectifier connected across the output of a mains transformer*

How the half-wave rectifier works

To help explain the operation of the half-wave rectifier, the circuit is redrawn in Figure 8 below with a resistor connected across its output terminals to represent a load.

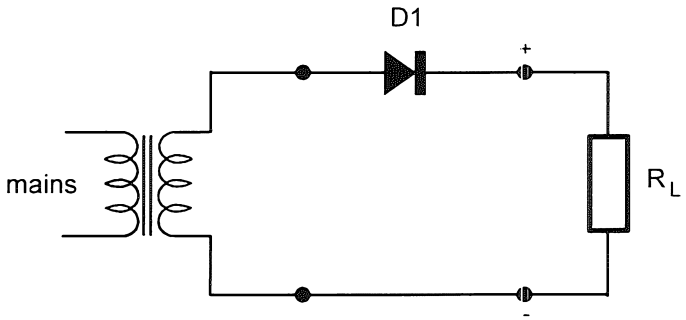

Figure 8 *The circuit of Figure 7 but with a load connected*

During the positive half cycle of the transformer's secondary voltage, the diode's anode is made positive with respect to its cathode and so it becomes forward biased once the secondary voltage exceeds about 0.6V.

When this happens, current flows through the diode and the load resistor in the direction shown in Figure 9. This develops a potential difference across the resistor in the polarity shown (hence the polarity of the circuit's output terminals).

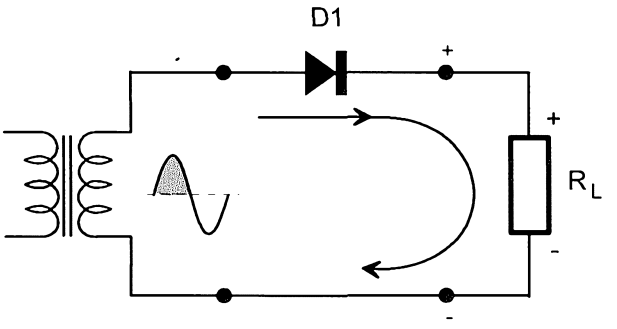

Figure 9

Then, during the negative half cycle of the transformer's secondary voltage, the diode's anode is made negative with respect to its cathode and so it is reverse biased. Recall that, when a diode is reverse biased, it acts like an open-circuit, so no current can flow through it (see Figure 10). This means that there is no potential difference developed across the load resistor during the negative half-cycle.

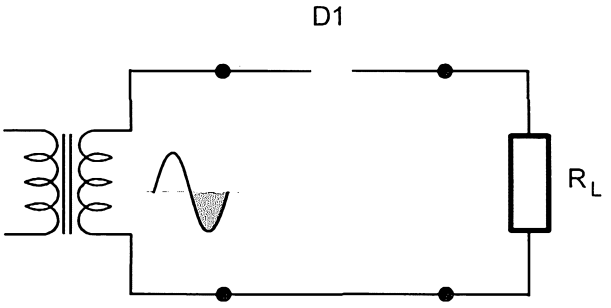

Figure 10

Over the entire cycle of the secondary voltage, the rectifier's output (which the load resistor is connected across) looks like the diagram in Figure 11 below.

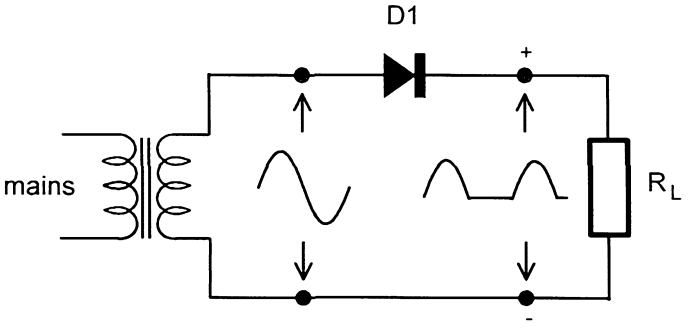

Figure 11 *The voltages on the input and output of a half-wave rectifier*

Figure 12 below shows the graphs for all the voltages and currents around the circuit of a half-wave rectifier time-coincident with the secondary voltage.

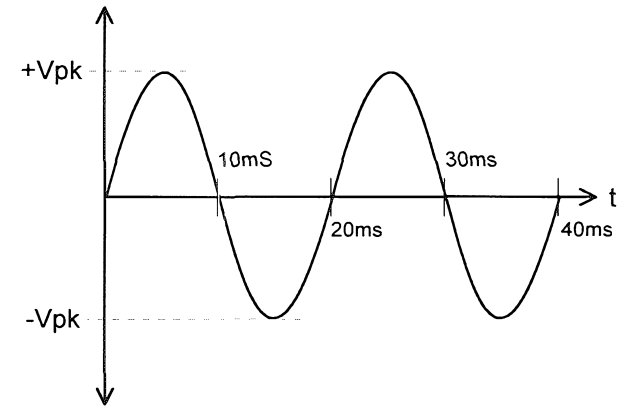

Figure 12a *The graph of the secondary voltage versus time*

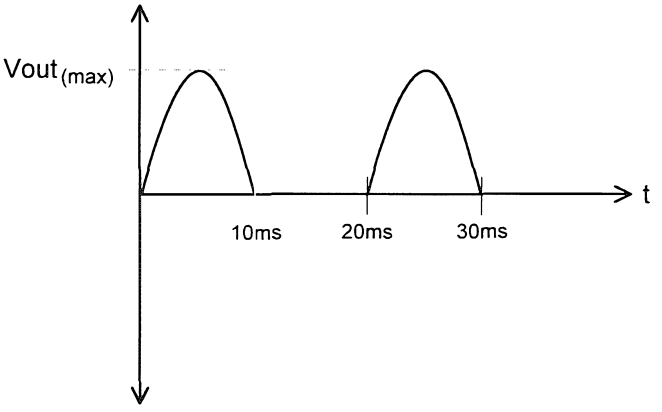

Figure 12b *The graph of output voltage (which is also the load voltage) versus time. Notice that the pulses of voltage coincide with the positive halves of the secondary voltage*

Notice also that the period of the output waveform is the same as the period of mains (20ms).

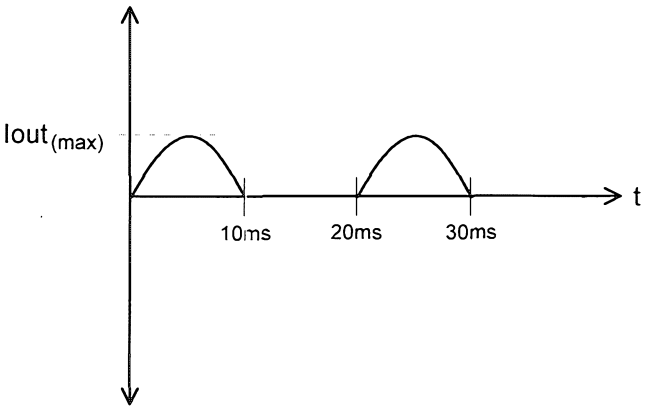

Figure 12c *The graph of circuit current versus time. Notice that current flows only during the positive halves of the secondary voltage.*

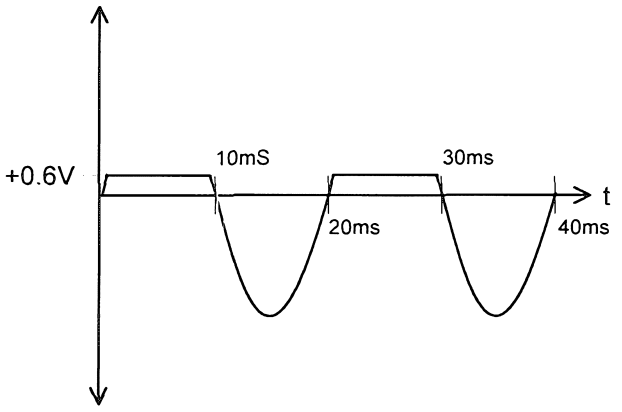

Figure 12d *The graph of the potential difference across the diode versus time. Notice that during the positive halves of the secondary voltage the potential difference across the diode only reaches 0.6V. But, during the negative halves of the secondary voltage the potential difference across the diode reaches the negative peak of the secondary voltage.*

There are a couple of interesting points to note about the graphs in Figure 12. First, notice that the pulses of DC at the output (see Figure 12b) coincide with the positive half cycles of the secondary. During the negative half-cycles of the secondary voltage, the output voltage is zero. Notice also that the output waveform's period is 20ms so the pulsating DC has a frequency of 50Hz ($f = \frac{1}{20ms}$).

Second, during the positive half cycle of the secondary voltage, the voltage across the diode only gets up to 0.6V, then the waveform "flat-lines" (see Figure 12d). This is because the diode is forward biased during this time and a forward biased diode always has a potential difference across it of about 0.6V.

Finally, during the negative half cycle of the secondary voltage when the diode is reverse biased, all of the secondary voltage is dropped across the diode (also see Figure 12d). This is despite the fact that there is no current flowing in the circuit at this time! While this might seem counter-intuitive, remember that Kirchhoff's Voltage Law still holds. So, if the potential difference across the load is zero then all of the secondary voltage must be being dropped across the diode.

Peak inverse voltage

The *peak inverse voltage* (PIV) is a special term used for the maximum potential difference across the diode when it is reverse biased. PIV is an important circuit parameter because if it exceeds the diode's reverse breakdown voltage the diode will conduct current in the direction that it's not supposed to do. If this happened, the diode's p-n junction can be permanently damaged and current would flow through the load in the wrong direction almost certainly damaging it too. As a rule, diodes are chosen so that their rated value of reverse breakdown voltage is two to three times greater than the PIV for the diode in the circuit.

The PIV occurs at the peak of the secondary waveform when the diode is turned off. This is shown in Figure 13 below.

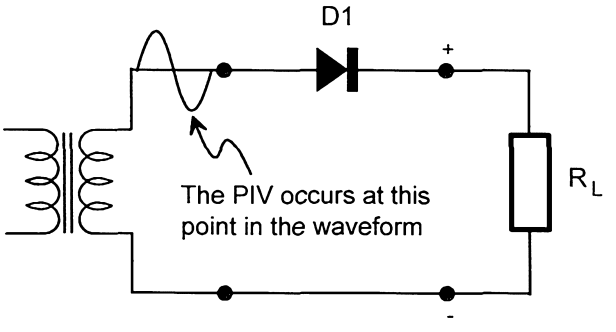

Figure 13 *The point in the secondary waveform at which the PIV occurs for a half-wave rectifier*

The PIV is calculated by finding the potential difference across the diode at this time. As you can see, when the PIV occurs the diode's anode is at the negative peak of the secondary voltage. At the same time, the potential difference across the load is 0V so the voltage on the diode's cathode is also 0V. These voltages are shown in Figure 14 below.

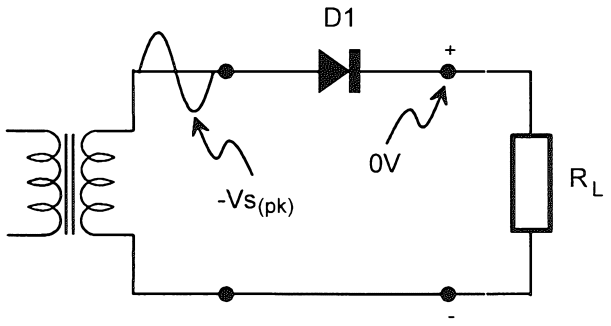

Figure 14 *The voltages around the circuit of a positive output voltage half-wave rectifier when the PIV occurs*

This diagram shows that the potential difference across the diode and hence the PIV of a half-wave rectifier (without smoothing) is the same as the negative peak of the secondary voltage.

$$PIV = -Vs_{(pk)}$$

Predicting the voltages and currents around the circuit

As a technician, you'll be expected to be able to repair DC power supplies. As they all include rectifier circuits then you'll need to be able to repair them. The process of locating faults in DC power supplies involves comparing measured voltages around the circuit with what they should be. As such, you need to be able to predict the voltages around the circuit by calculation.

In addition to this, diodes sometimes have to be substituted with equivalents because the original part is no-longer available or is too expensive. To make a decision about whether or not a particular diode is an appropriate equivalent, the currents in the circuit must be known. As such, you also need to be able to calculate the currents around the circuit of a half-wave rectifier.

1. Input voltage

   Finding the input voltage to a rectifier circuit involves finding the transformer's secondary voltage. Recall that the transformer's secondary voltage is found using the equation:

$$Vs = \frac{V_P}{N}$$

   An important point to make here is that, as you will see, we're only really interested in the secondary voltage's peak value. But, if the primary voltage that you use in the equation above is quoted in RMS then the secondary voltage will also be in RMS. If this is the case, you should convert the primary voltage to a peak value before you use the equation above or convert the secondary voltage to a peak value after you've used it.

2. Output voltage

   We're interested in two voltage measurements that can be made at the output of rectifier circuits: a) the maximum output voltage which is also the maximum load voltage (measured by a CRO); and b) the average output voltage which is also the average load voltage (measured by a multimeter).

   The maximum output voltage ($Vout_{(max)}$) of a rectifier circuit is the voltage at the top of the output waveform. Although it is a peak value, it's not called the peak voltage to avoid confusing it with the peak voltage of the secondary.

   As the rectifier diode and the load resistor are in series then Kirchhoff's Voltage Law (KVL) applies to the circuit. Recall that KVL states that the potential differences of the components in a series circuit add up to the supply voltage. Furthermore, as diodes have a potential difference of 0.6V when forward biased, the maximum output voltage is:

$$Vout_{(\max)} = Vs_{(pk)} - 0.6V$$

Once the maximum output voltage is known, the average output voltage ($Vout_{(av)}$) can be calculated using the equation:

$$Vout_{(av)} = Vout_{(\max)} \times 0.318$$

3. The maximum output current

As the circuit of a half-wave rectifier is a series circuit, the output current, diode current and load current are all the same. The maximum output current ($Iout_{(max)}$) can be found using Ohm's Law.

$$Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$$

4. The average output current

This current ($Iout_{(av)}$) can also be found using Ohm's Law.

$$Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$$

An alternative method for finding the average output current is to use the equation:

$$Iout_{(av)} = Iout_{(\max)} \times 0.318$$

Let's do an example.

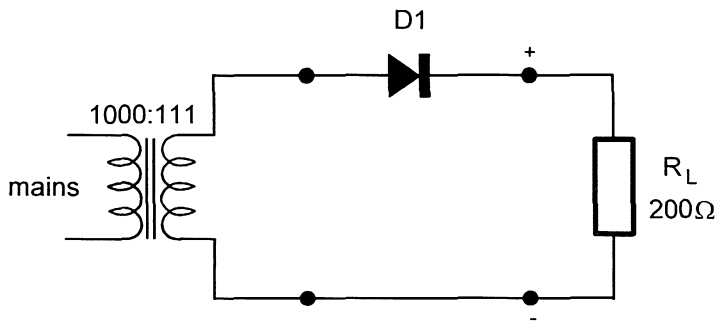

Figure 15

For the circuit in Figure 15 above the peak primary voltage must calculated first. As mains is 240V RMS:

$$Vp_{(pk)} = Vp \times 1.414$$

$$Vp_{(pk)} = 240V \times 1.414$$

$$Vp_{(pk)} = 339.4V$$

Next, the transformer's turns ratio is calculated:

$$N = \frac{N_P}{N_S}$$

$$N = \frac{1000}{111}$$

$$N = 9$$

The transformer's turns ratio is then used to find its secondary voltage:

$$Vs = \frac{V_P}{N}$$

$$Vs = \frac{339.4Vpk}{9}$$

$$Vs = 37.7Vpk$$

Next, find the maximum output voltage:

$$Vout_{(\max)} = Vs_{pk} - 0.6V$$

$$Vout_{(\max)} = 37.7Vpk - 0.6V$$

$$Vout_{(\max)} = 37.1V$$

Then find the average output voltage:

$$Vout_{(av)} = Vout_{(\max)} \times 0.318$$

$$Vout_{(av)} = 37.1V \times 0.318$$

$$Vout_{(av)} = 11.8V$$

And finally the maximum and average output currents:

$$Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$$

$$Iout_{(\max)} = \frac{37.1V}{200\Omega}$$

$$Iout_{(\max)} = 185.5mA$$

$$Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$$

$$Iout_{(av)} = \frac{11.8V}{200\Omega}$$

$$Iout_{(av)} = 59mA$$

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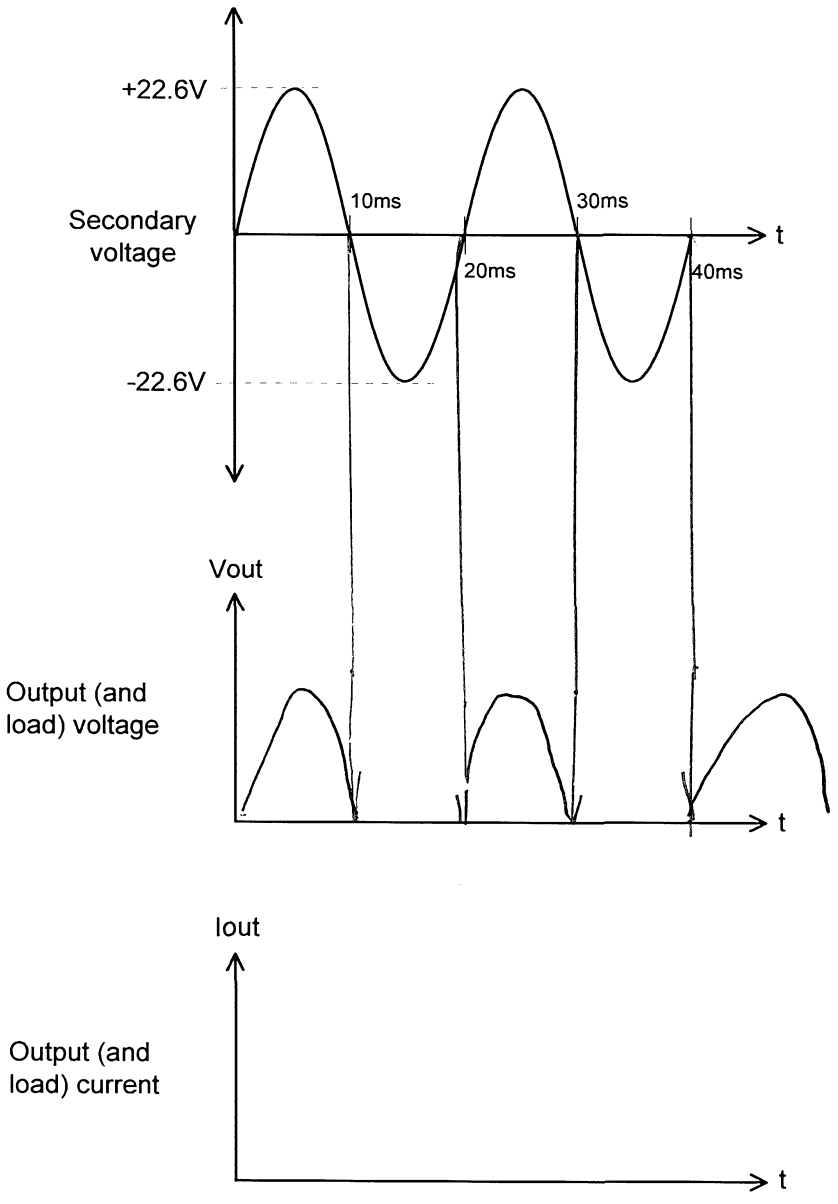
6. What is the diode's PIV in the circuit?

PIV = 22.6V

7. What should the diode's rated reverse breakdown voltage be?

At least 50V

8. In the space below, draw the voltage and current waveforms across the load, time coincident with the secondary voltage. Show all voltage and time information.



Practise calculating the voltages and currents around a half-wave rectifier by trying the following questions.

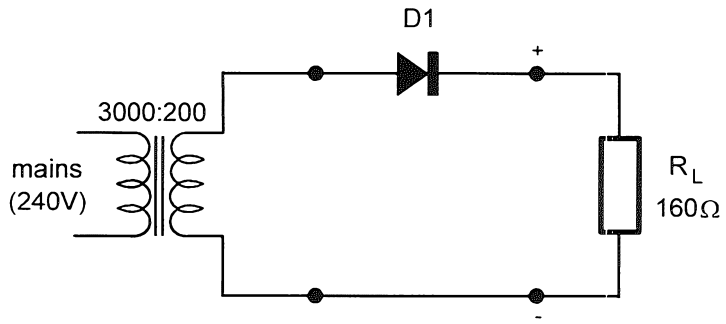


Figure 16

1. Calculate the peak secondary voltage (*Vs*). **Tip:** Convert mains to a peak value first!

$V_{S(RMS)} = V_{S(PEAK)} = 16 \times \sqrt{2} \approx 22.6V$

$\approx 16 V_{AC(RMS)}$

2. Calculate the maximum output voltage ($Vout_{(max)}$).

$V_S - V_D = 22.6 - 0.7 = 21.9V$

3. Calculate the average output voltage ($Vout_{(av)}$).

$\frac{V_{OUT(MAX)}}{\pi} = \frac{21.9}{3.142} = 7V$

4. Calculate the maximum output current ($Iout_{(max)}$).

$\frac{V_{OUT(MAX)}}{R_L} = \frac{21.9}{160} = 137mA$

5. Calculate the average output current ($Iout_{(av)}$).

$\frac{V_{OUT(AV)}}{R_L} = \frac{7}{160} = 43.8mA$

Negative output voltages

The half-wave rectifier discussed so far provides a positive output voltage. The circuit can be modified to provide a negative output voltage by simply reversing the rectifier diode's polarity. This is shown in Figure 17 below.

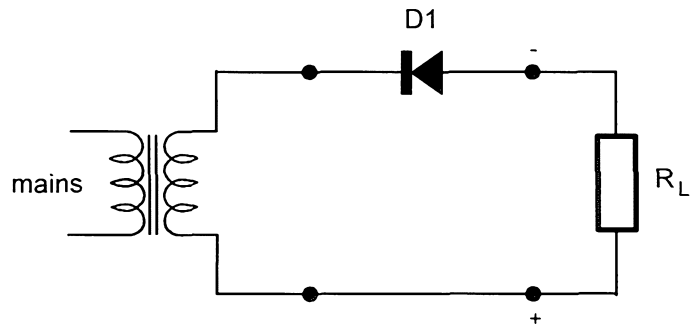


Figure 17 *A half-wave rectifier circuit that provides a negative output voltage instead of a positive voltage*

How the circuit works

During the positive half cycle of the transformer's secondary voltage, the diode's cathode is made positive with respect to its anode and so it is reverse biased. This means that the diode acts like an open-circuit (see Figure 18) so no current can flow through it and there is no potential difference developed across the load resistor.

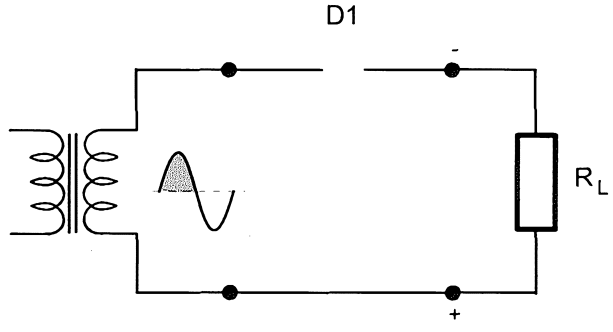


Figure 18

Then, during the negative half cycle of the transformer's secondary voltage, the diode's cathode is made negative with respect to its anode and so it becomes forward biased once the secondary voltage exceeds about -0.6V.

When this happens, current flows through the diode and the load resistor in the direction shown in Figure 19. This develops a potential difference across the resistor in the polarity shown (hence the polarity of the circuit's output terminals).

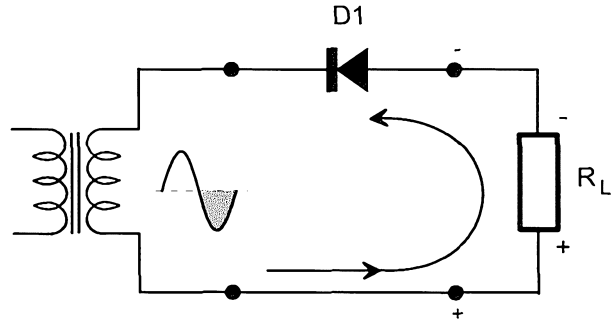


Figure 19

Over the entire cycle of the secondary voltage, the rectifier's output looks like the diagram in Figure 20 below.

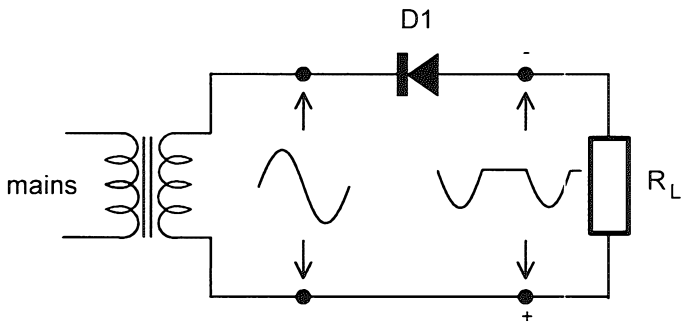


Figure 20 *The voltages on the input and output of a negative output voltage half-wave rectifier*

The calculations for voltages and currents around the circuit are identical to the calculations for the positive output voltage half-wave rectifier except the negative peak voltage of the secondary is used to calculate the maximum output voltage ($Vout_{(max)}$) instead of the positive peak voltage. Also, the PIV is equal to the voltage at the positive peak of the secondary instead of the negative peak (that is, $PIV = Vs_{(pk)}$).

Faults in the simple half-wave rectifier circuit

As there is only one component in this circuit that can only basically go short or open, there are only two possible faults: 1) Open-circuit rectifier diode - This results in no output voltage; or 2) Short-circuit rectifier diode - This results in the full secondary voltage appearing at the output (that is, no rectification).

Substituting rectifier diodes

For equipment manufactured overseas you may find it difficult (or costly) to replace a faulty component with an original part. This is often also true of older equipment. In these situations, it may be possible to replace the faulty component with a more easily available and/or cheaper substitute.

For rectifier circuits, this is relatively easy and safe to do as long as you have the electrical specifications of both the original part and the diode that you're thinking of replace it with. If this is the case, the two most important specifications of rectifier diodes to match are the forward current (I_F) and the reverse breakdown voltage (V_R) - The teacher will show you examples of rectifier diode data sheets. Compare these specifications and ensure that the substitute diode's ratings are at least as good as the original part.

If you don't have the electrical specifications of the original part (which is a common problem) all is not lost. The maximum circuit current ($Iout_{(max)}$) for the circuit and the peak inverse voltage (PIV) that the diode experiences can be calculated (as you have seen) and this information can be used to choose any rectifier diode with an appropriate forward current and reverse breakdown voltage ratings. As already mentioned, always choose a diode with a reverse breakdown voltage two or three times larger than the PIV.

Advantages and disadvantages of the half-wave rectifier

The advantage of the half-wave rectifier (over the other rectifiers which will be covered in the next section) is simplicity. The circuit only requires one component which also makes the half-wave rectifier cheap to make. For these reasons, the half-wave rectifier is often used for mains operated battery-chargers.

However, as you will see, the big gap between the pulses of DC at the output of the half-wave rectifier requires smoothing circuitry that is physically much larger than the smoothing circuitry of the full-wave rectifiers. This may be a problem where size is an issue (but not for battery chargers as smoothing circuitry is not needed).

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Student notes

Skill practice 2

Practise measuring diode operating conditions in half-wave rectifier circuits (both functional and faulty) using an AMM and an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1½ hours to complete this exercise.

Equipment

- 15V AC power supply
- Interface panel
- analog multimeter (AMM)
- 1N4004 diode
- 150Ω 5W resistor
- two BNC to alligator-clip leads
- banana leads

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the interface panel using the 15V AC power supply for the transformer in the circuit.

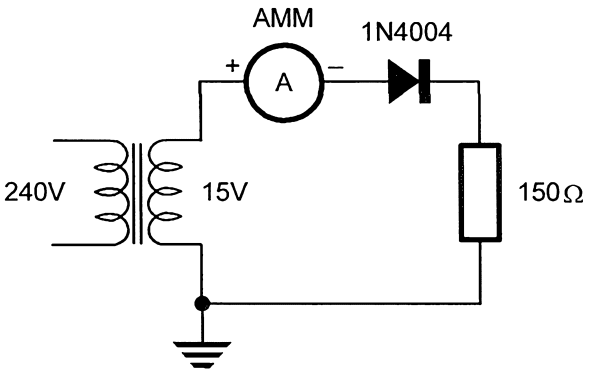


Figure 1

4. Turn on the AC power supply and use the DMM to measure the potential difference across the transformer's secondary. Record your measurement in Table 1 below.

   Note: The voltage will higher than 15V indicated in Figure 1 but that's ok.

5. Use the **measured** secondary voltage to calculate and record the peak secondary voltage.

6. Use the peak secondary voltage to calculate and record the rectifier's maximum output voltage $Vout_{(max)}$.

7. Use the $Vout_{(max)}$ to calculate and record the rectifier's average output voltage ($Vout_{(av)}$).

8. Use the $Vout_{(av)}$ to calculate and record the rectifier's average output current ($Iout_{(av)}$).

Table 1

Measured secondary voltage (RMS)	
Calculated secondary voltage (peak)	
Calculated $Vout_{(max)}$	
Calculated $Vout_{(av)}$	
Calculated $Iout_{(av)}$	

9. Turn off the AC power supply.

10. Connect the CRO's channel 1 input across the load resistor (connect the black alligator clip of the CRO lead to the circuit common/earth).

11. Set the CRO's channel 1 vertical attenuation control to the *5V/div* position.

12. Set the CRO's channel 1 input coupling control to the *GND* position.

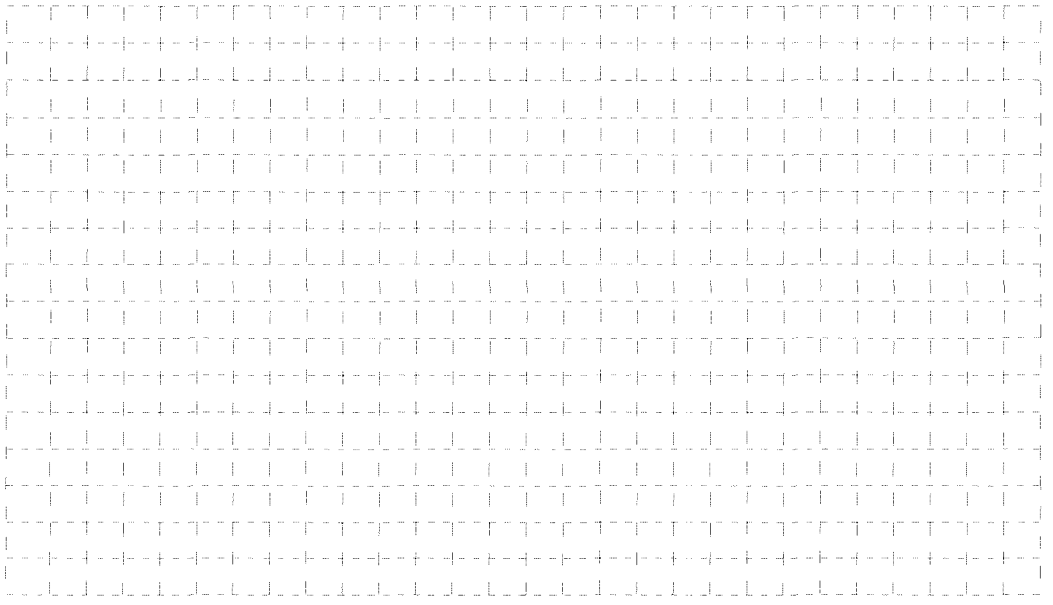
13. Move the CRO's trace so that it's aligned with the horizontal line that's second from the bottom of the graticule.

    Note: Once you've done this, you'll know where zero volts is on the graticule so don't move the trace's vertical position after performing this step.

14. Set the CRO's channel 1 input coupling control to the *DC* position.

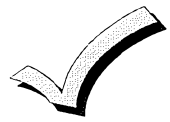
15. Turn on the AC power supply.

16. Draw the voltage across the load on the graph below.



17. Use the CRO to measure as accurately as possible the rectifier's maximum output voltage $Vout_{(max)}$ and show this on your drawing above.

18. Use the CRO to measure the waveform's period and show this on your drawing above.



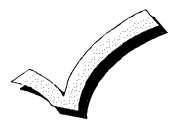
The teacher needs to check your work at this point...

Question 1
Why doesn't the negative half cycle of the secondary voltage appear across the load resistor?

Question 2
Is the voltage across the load resistor AC or DC? Explain your answer.

Question 3
How do your calculated and measured values of $Vout_{(max)}$ compare? Explain any differences.

Question 4
Use the load waveform's measured period to calculate its frequency.



The teacher needs to check your work at this point...

19. Use the AMM to measure the load current. Record your measurement in the appropriate space in Table 2 below.

20. Disconnect the AMM and use it to measure and record the potential difference across the load.

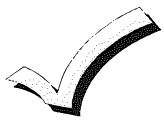
Table 2

Measured load voltage	
Measured load current	

Question 5
What type of voltage and current has the AMM measured?

- ☐ Peak-to-Peak
- ☐ Average
- ☐ RMS
- ☐ Peak

Question 6
Compare the theoretical values (Table 1) and measured values (Table 2) of potential difference and current. Are they the same? What might cause any differences?



The teacher needs to check your work at this point...

21. Turn off the AC power supply.

22. Connect a wire across the diode. This simulates a short-circuit diode.

23. Turn on the power supply.

24. Observe the secondary voltage and potential difference across the resistor on the CRO.

Question 7
What happens to the potential difference across the load when the diode is a short-circuit and why does this happen?

_____

_____

_____

25. Turn off the AC power supply.

26. Remove the short from across the diode and disconnect one of the diode's legs from the circuit. This simulates an open-circuit diode.

27. Turn on the power supply.

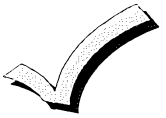
28. Observe the secondary voltage and potential difference across the resistor on the CRO.

Question 8
What happens when the diode is an open-circuit and why does this happen?

_____

_____

_____



The teacher needs to check your work at this point...

29. Turn off the AC power supply.

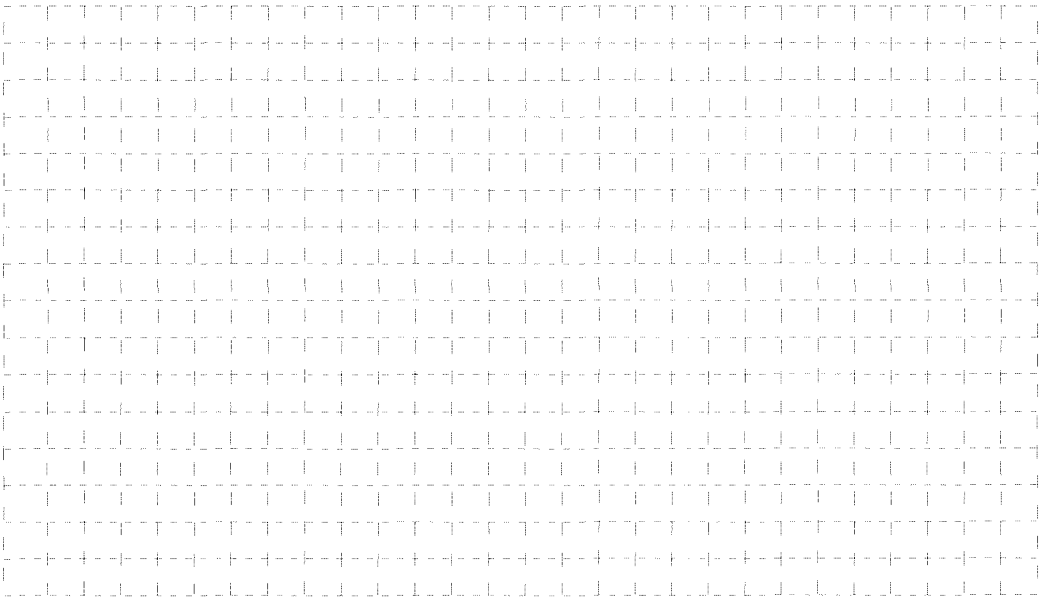
30. Reverse the diode's polarity.

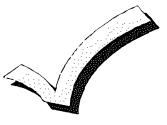
31. Turn on the AC power supply.

32. Use the CRO to look at the potential difference across the load resistor again.

33. Draw voltage across the load on the graph below.

34. Momentarily set the channel 1 input coupling control to the *GND* position and note where the 0V line occurs in relation to the waveform. Show the 0V line on your drawing.





The teacher needs to check your work at this point...

Question 9
Draw the schematic diagram of the modified circuit.

Question 10
Show the direction of current around the circuit and the polarity of the potential difference across the load on the schematic diagram you've just drawn.

Question 11
In what way would the average output voltage of this rectifier (that is, the load voltage measured by the meter) be different to the measured average output voltage of the circuit in Figure 1?

The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. Draw the generic block diagram of a power supply.

2. Which block is responsible for converting the AC to DC?

   ☐ The isolation and step-down block
   ☐ The rectification block
   ☐ The smoothing block
   ☐ The regulation block

3. Which block is responsible for keeping the output voltage as steady as possible as the load varies?

   ☐ The isolation and step-down block
   ☐ The rectification block
   ☐ The smoothing block
   ☐ The regulation block

4. Which block is responsible for producing a steady state DC?

   ☐ The isolation and step-down block
   ☐ The rectification block
   ☐ The smoothing block
   ☐ The regulation block

5. What are the two purposes of the transformer in a power supply?

6. Draw the circuit of a half-wave rectifier with a positive output voltage.

7. Draw the circuit of a half-wave rectifier with a negative output voltage.

Questions 8 to 17 refer to the circuit in Figure 1 below

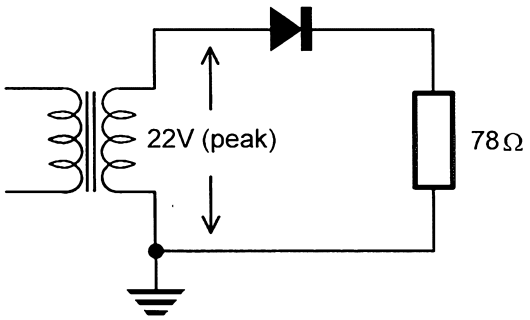

Figure 1

8. What is the maximum potential difference across the resistor ($Vout_{(max)}$)?

9. Draw the waveforms of the secondary voltage and the potential difference across the resistor time coincident with each other. Show all voltages and times on your graphs.

10. What is the frequency of the pulsating DC across the load?

11. What is the average potential difference across the resistor ($Vout_{(av)}$)?

12. What is the maximum current through the resistor ($Iout_{(max)}$)?

13. What is the average current through the resistor ($Iout_{(av)}$)?

14. Current flows through the resistor during

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

15. What is the *peak inverse voltage* across the diode?

16. What rated value of *reverse breakdown voltage* should the diode have?

17. The peak inverse voltage across the diode occurs at the peak of

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

Questions 18 to 22 refer to the circuit in Figure 2

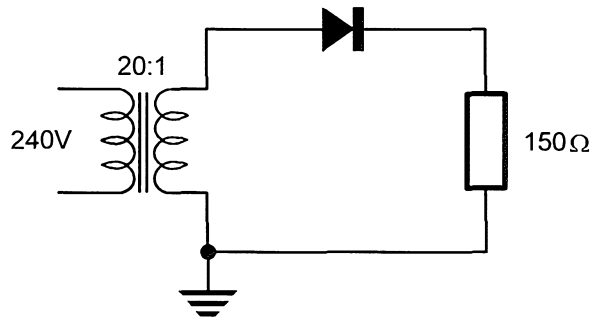

Figure 2

18. What is the maximum potential difference across the resistor ($Vout_{(max)}$)?

19. What is the average potential difference across the resistor ($Vout_{(av)}$)?

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20. What is the maximum current through the resistor ($Iout_{(max)}$)?

21. What is the average current through the resistor ($Iout_{(av)}$)?

22. What is the PIV across the diode?

Questions 23 to 27 refer to the circuit in Figure 3

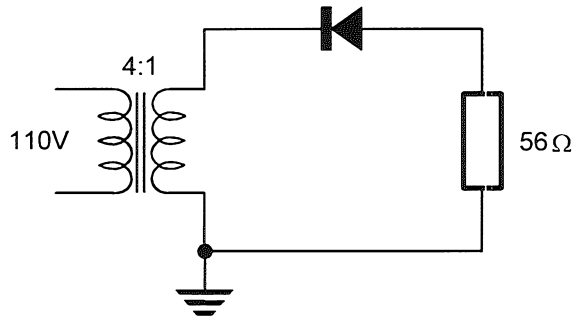

Figure 3

23. What is the maximum potential difference across the resistor ($Vout_{(max)}$)?

24. What is the average potential difference across the resistor ($Vout_{(av)}$)?

25. What is the maximum current through the resistor ($Iout_{(max)}$)?

26. What is the average current through the resistor ($Iout_{(av)}$)?

27. Current flows through the resistor during

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

28. What is the PIV across the diode?

29. What is one advantage and one disadvantage of the half-wave rectifier?

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Student notes

Section 3 Full-wave rectification

Purpose To develop your ability to use test equipment to test full-wave rectifier circuits, recognise when the circuit is faulty, and identify the likely faulty component.

Objectives At the end of this section you should be able to:

- Draw the circuit of a centre-tapped transformer full-wave rectifier and a bridge rectifier to produce a positive or negative output voltage
- Show the current paths during each half cycle of the transformer's secondary voltage through the circuit of the two full-wave rectifier circuits
- Draw the potential difference and current waveforms for the load of the two full-wave rectifier circuits
- State the frequency of the potential difference and current waveforms for the load of the two full-wave rectifier circuits
- Calculate the maximum values of potential difference and current for the load of the two full-wave rectifier circuits given the transformer's primary voltage and turns ratio
- Calculate the average potential difference and current for the load of the two full-wave rectifier circuits given maximum values for each
- Draw the waveform of the potential difference across the diodes in the two full-wave rectifier circuits
- Calculate the peak inverse voltage of the two full-wave rectifier circuits given the transformers primary voltage and turns ratio
- Choose diodes with suitable specifications for the reverse breakdown voltage and forward current for the two full-wave rectifier circuits given the load resistance
- State an advantage and a disadvantage of the two full-wave rectifier circuits
- Use a DMM and an oscilloscope to perform measurements of rectifier diode operating conditions in full-wave rectifier circuits

Introduction

The last section showed that there are four basic functional blocks in all power supplies. The second of these is the rectification block. Rectification converts the secondary voltage of the transformer (which is AC) to a pulsating DC voltage. There are three circuits that can perform rectification and the last section explained the operation of one of them in detail (the half-wave rectifier). This section explains the operation of the other two.

Full-wave rectifier circuits

There are two circuits that can perform full-wave rectification of AC voltages and they are:

- the centre-tapped transformer full-wave rectifier
- the bridge rectifier

There is a significant advantage of both full-wave rectifiers over the half-wave rectifier. The circuitry required to smooth out the pulsing DC from a full-wave rectifier (a task performed by the third functional block) can be physically smaller (for the same amount of smoothing) because the pulses of DC are twice as frequent. This issue is discussed in detail in the next section.

The centre-tapped transformer full-wave rectifier

Figure 1 below shows the circuit of a full-wave rectifier connected across the output of a centre-tapped mains transformer. As you can see, the full-wave rectifier circuit consists of two diodes.

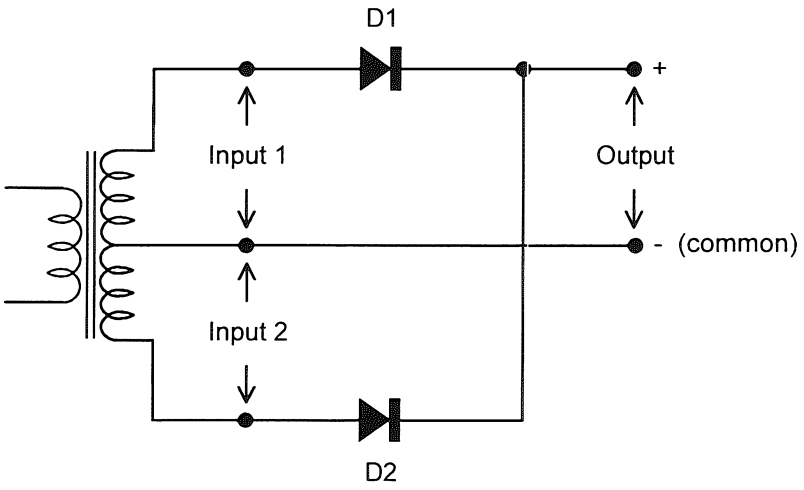


Figure 1 *A full-wave rectifier connected across the output of a centre-tapped mains transformer*

How the centre-tapped transformer full-wave rectifier works

To fully explain the circuit's operation, we need to redraw it showing a resistor connected across the output terminals to represent a load. This is shown in Figure 2 below.

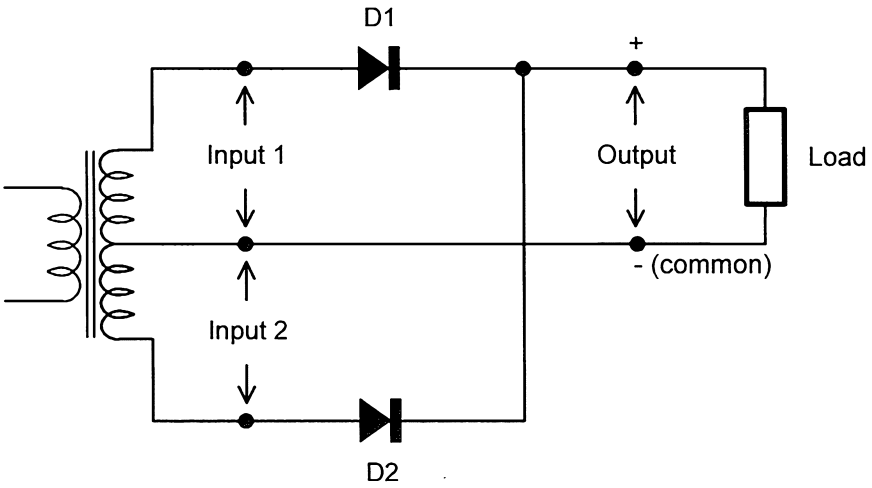


Figure 2 *The circuit of Figure 1 but with a load connected*

Recall from your earlier in AC theory that the voltage on the ends of a centre-tapped transformer are phase inverted relative to each other if the voltages are measured with respect to the centre-tap. This is shown in Figure 3 below.

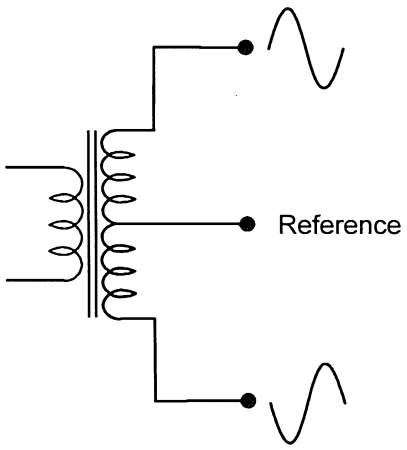


Figure 3 *In relation to the centre-tap, the outputs of a centre-tapped transformer are phase inverted*

This phase relationship between the transformer's two outputs is crucial to the operation of the centre-taped transformer full-wave rectifier circuit.

During the first half cycle of both waveforms, the anode of *D1* is positive with respect to its cathode but the anode of *D2* is negative with respect to its cathode. This means that *D1* is forward biased and conducts current but *D2* is reverse biased and looks like an open-circuit. This is shown in Figure 4 below. Importantly, the current through *D1* travels through the load (also shown in Figure 4) and develops a potential difference across it in the polarity shown.

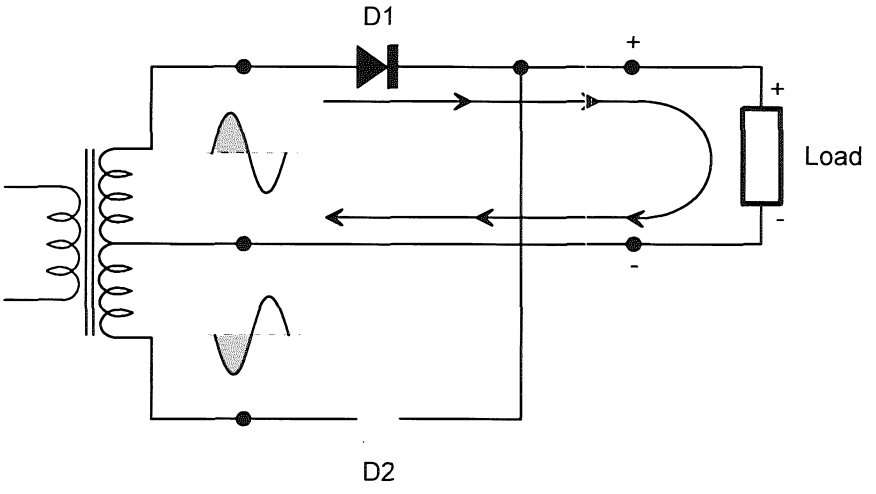


Figure 4 *The current in the circuit when the output of the upper secondary winding is positive*

During the second half cycle of both waveforms, the anode of *D1* is negative with respect to its cathode but the anode of *D2* is positive with respect to its cathode. This means that *D1* is reverse biased and looks like an open-circuit while *D2* is forward biased and conducts current in the direction shown in Figure 4 below. Importantly, this current travels through the load in the same direction as the current during the first half cycle, so the polarity of the potential difference across the load is also the same.

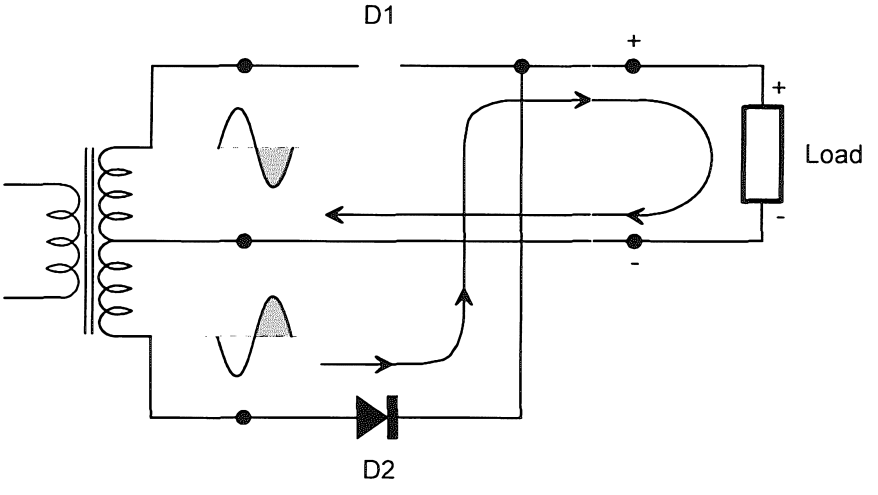


Figure 5 *The current in the circuit when the output of the lower secondary winding is positive*

Figure 6 shows the graphs for the output voltage and current in the circuit of a centre-tapped transformer full-wave rectifier time-coincident with the two secondary voltages.

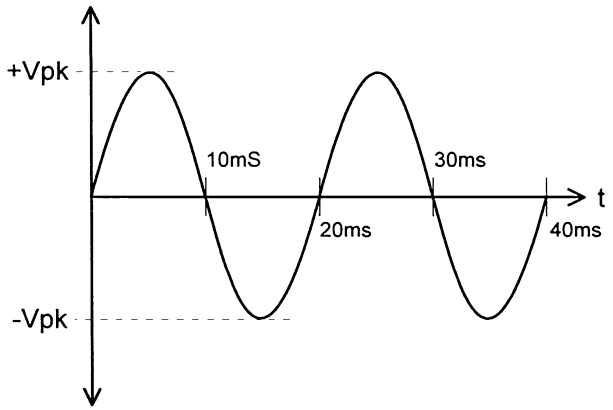


Figure 6a *The graph of the upper secondary voltage versus time*

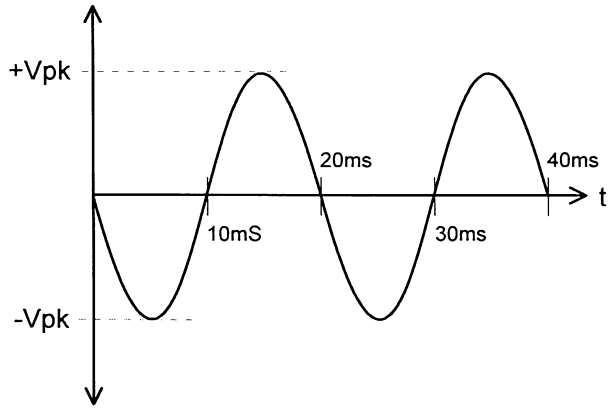


Figure 6b *The graph of the lower secondary voltage versus time*

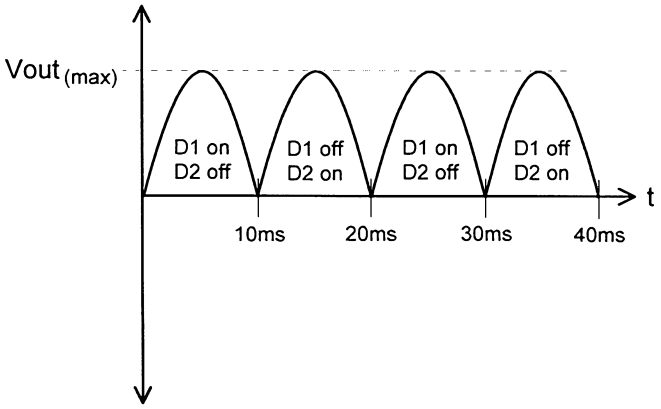


Figure 6c *The graph of output voltage (which is also the load voltage) versus time. Notice that there are twice as many pulses compared to the half-wave rectifier*

Notice also that the period of the output waveform is half the period of mains (that is, 10ms instead of 20ms)

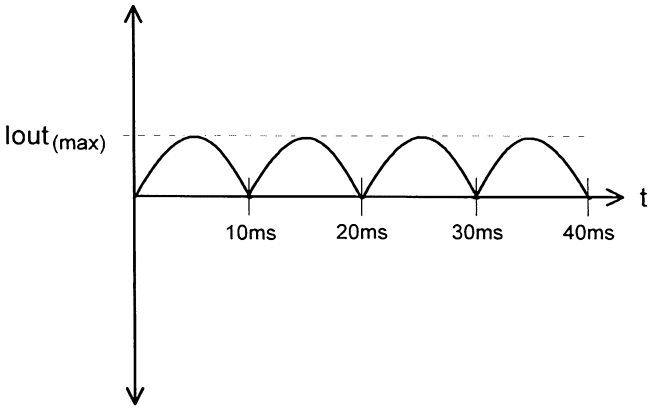


Figure 6d *The graph of circuit current (which is also the load current) versus time*

Peak inverse voltage

As just explained, the two diodes in the centre-tapped transformer full-wave rectifier are periodically reverse biased. At the peak of the secondary voltage when the diodes are off they'll experience the peak inverse voltage (PIV). But, as the diodes are turned off at different times, the PIV of each diode occurs at different times as well. This is shown in Figure 7 below.

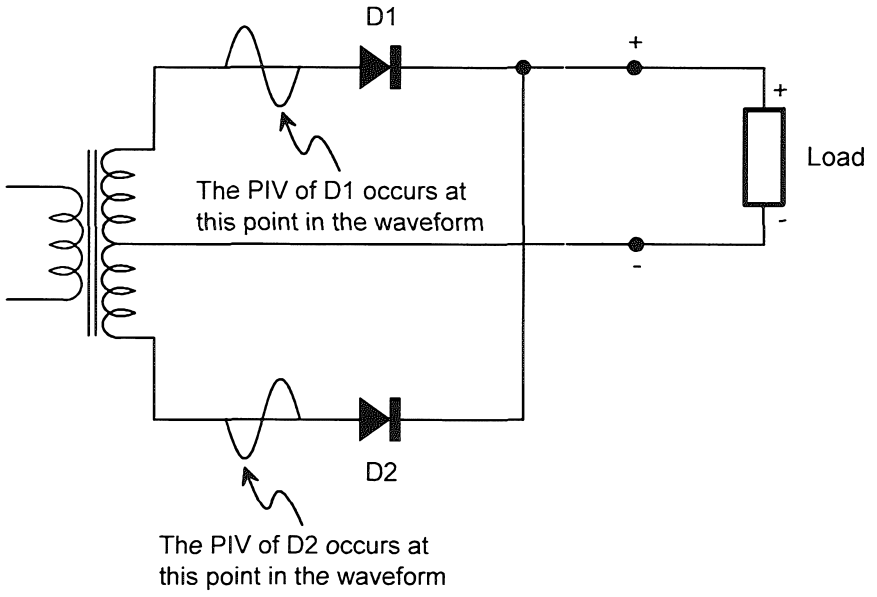


Figure 7 *The point in the two secondary waveforms when the diodes experience the PIV*

When either diode is turned off and its anode is going negative, the other diode is turned on and as the cathodes of both diodes' are connected together, both cathodes are going positive. This as shown in Figure 8 below when *D1* is off.

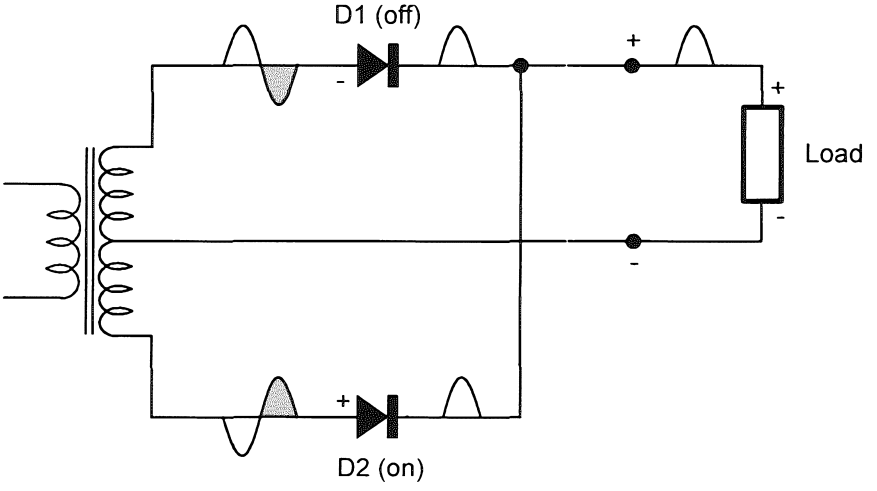


Figure 8 *The voltages around the circuit when D1 is off and D2 is on*

Importantly, when the PIV for *D1* occurs, the potential difference across the load reaches the maximum output voltage as shown in Figure 9 below.

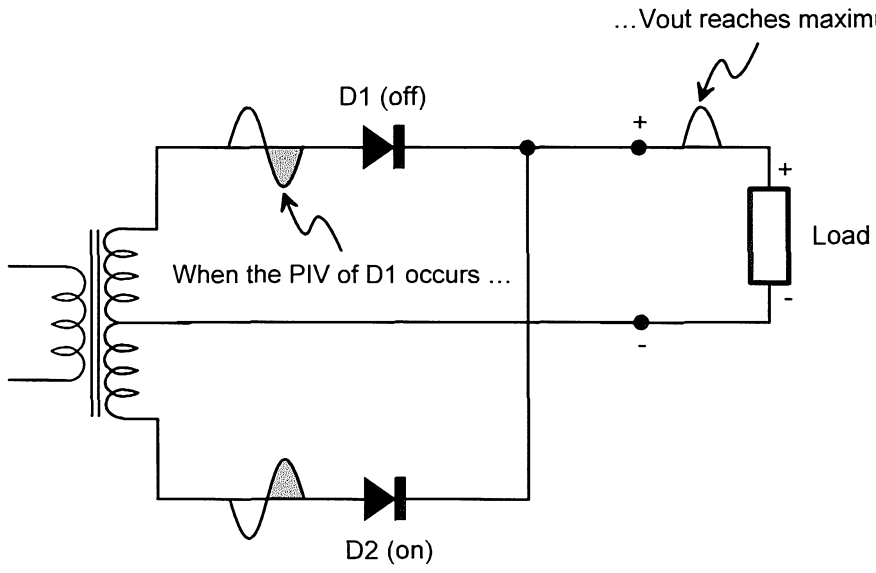


Figure 9 *The voltages around the circuit when the PIV of D1 occurs*

This means that while the cathode of *D1* is at the negative peak of the secondary voltage, its anode is at a voltage very close to the positive peak of secondary voltage. That being the case, the potential difference across *D1*, and hence its PIV, is approximately equal to twice the peak secondary voltage. This analysis is also true for the PIV for *D2*.

So, we can say that for a centre-tapped transformer full-wave rectifier, the size of the PIV that the diodes experience is equal to:

$$PIV = 2 \times Vs_{(pk)}$$

Predicting the voltages and currents around the circuit

As with half-wave rectifier circuits, you need to be able to calculate the voltages and currents around the circuit of a full-wave rectifier.

1. Input voltage (Vs)

   This is calculated in the same way as calculating the input voltage to the half-wave rectifier.

$$Vs = \frac{V_P}{N}$$

2. The maximum output voltage ($Vout_{(max)}$)

   This voltage is also the maximum load voltage and is calculated in the same way as calculating the maximum output voltage of the half-wave rectifier.

$$Vout_{(\max)} = Vs_{(pk)} - 0.6V$$

   Note: Although there are two diodes in the centre-tapped transformer full-wave rectifier, only one of them is ever turned on at a time so the maximum output voltage is smaller than the peak secondary voltage by only one diode forward voltage drop.

3. The average output voltage ($Vout_{(av)}$)

   This voltage is also the average load voltage and, once the maximum output voltage is known, the average output voltage ($Vout_{(av)}$) can be calculated using the equation:

$$Vout_{(av)} = Vout_{(\max)} \times 0.636$$

   Notice that the calculation for the average output voltage for a full-wave rectifier is different to the calculation for the half-wave rectifier (recall that for a half-wave rectifier the equation is $Vout_{(av)} = Vout_{(\max)} \times 0.318$). As there are twice as many pulses on the output of the full-wave rectifier, the average voltage is twice as big. Hence, 0.636 is two times 0.318.

4. The maximum output current ($Iout_{(max)}$)

   This is also the maximum load current and is calculated in the same way as calculating the maximum output current of the half-wave rectifier.

$$Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$$

5. The average output current ($Iout_{(av)}$)

   This is also the average load current and is calculated in the same way as calculating the average output current of the half-wave rectifier.

$$Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$$

An alternative method for finding the average output current is to use the equation:

$$Iout_{(av)} = Iout_{(\max)} \times 0.636$$

Let's do an example.

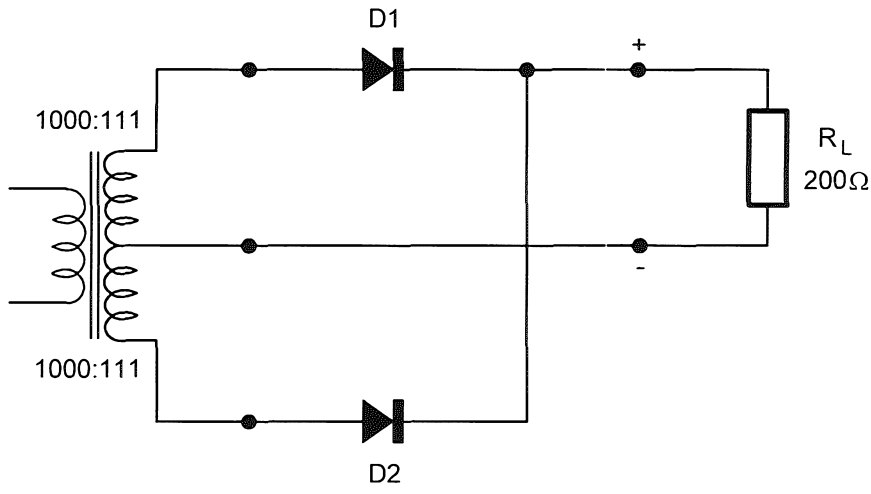


Figure 10

For the circuit in Figure 10 above we first find the peak primary voltage. As we know, mains is 240V RMS so:

$$Vp_{(pk)} = Vp \times 1.414$$

$$Vp_{(pk)} = 240V \times 1.414$$

$$Vp_{(pk)} = 339.4V$$

Next, we need to find the transformer's turns ratio for both secondaries:

$$N = \frac{N_P}{N_S}$$

$$N = \frac{1000}{111}$$

$$N = 9$$

And now we can find the transformer's secondary voltage:

$$Vs = \frac{V_P}{N}$$

$$Vs = \frac{339.4Vpk}{9}$$

$$Vs = 37.7Vpk$$

Next, find the maximum output voltage:

$$Vout_{(\max)} = Vs_{(pk)} - 0.6V$$

$$Vout_{(\max)} = 37.7Vpk - 0.6V$$

$$Vout_{(\max)} = 37.1V$$

Now we can find the average output voltage:

$$Vout_{(av)} = Vout_{(\max)} \times 0.636$$

$$Vout_{(av)} = 37.1V \times 0.636$$

$$Vout_{(av)} = 23.6V$$

And the maximum and average output currents:

$$Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$$

$$Iout_{(\max)} = \frac{37.1V}{200\Omega}$$

$$Iout_{(\max)} = 185.5mA$$

$$Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$$

$$Iout_{(av)} = \frac{23.6V}{200\Omega}$$

$$Iout_{(av)} = 118mA$$

Practise calculating the voltages and currents around a centre-tapped transformer full-wave rectifier by trying the following questions.

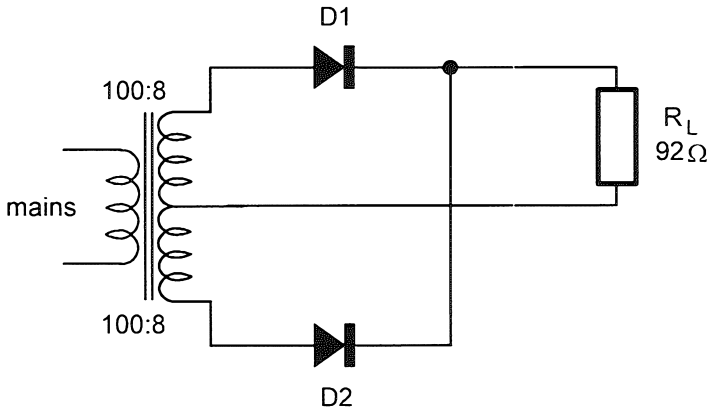


Figure 11

1. What is the peak secondary voltage (*Vs*)?

2. What is the maximum output voltage ($Vout_{(max)}$)?

3. What is the average output voltage ($Vout_{(av)}$)?

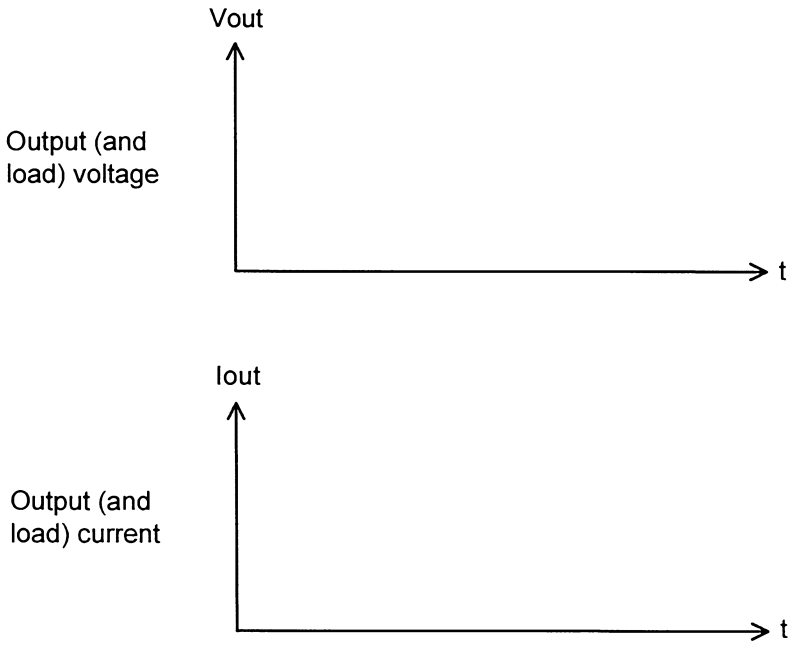
4. What is the maximum output current ($Iout_{(max)}$)?

5. What is the average output current ($Iout_{(av)}$)?

6. What is the size of the PIV that the diodes' experience?

7. What should the diodes' rated reverse breakdown voltage be?

8. In the space below, draw the voltage and current waveforms across the load. Show all voltage and time information.



Negative output voltages

The centre-tapped transformer full-wave rectifier that we have looked at so far provides a positive output voltage. By simply reversing the polarity of the rectifier diodes we can modify the circuit to provide a negative output voltage. This is shown in Figure 12 below.

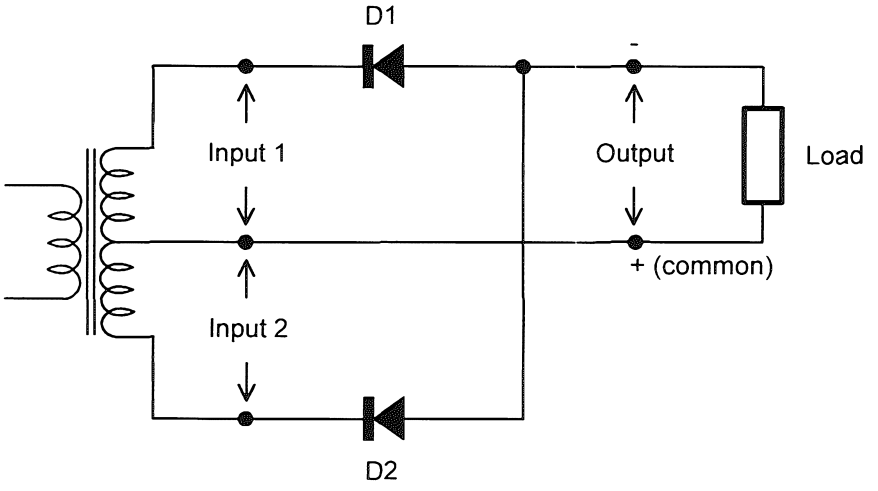


Figure 12 *A centre-tapped transformer full-wave rectifier circuit that provides a negative output voltage instead of a positive voltage*

The polarity of the diodes in this circuit are such that, whenever they're forward biased, current always travels up through the load from the common line. This means that the potential difference across the load is negative with respect to common.

Figure 13 below shows what the output voltage would look like if viewed on a CRO.

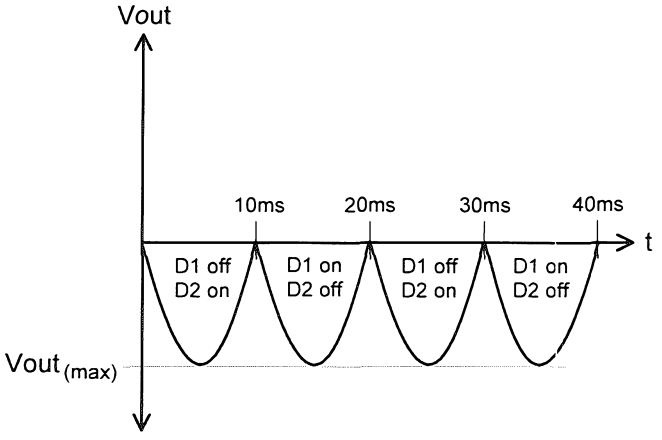


Figure 13 *The output voltage from the rectifier circuit in Figure 12*

Faults in the centre-tapped transformer full-wave rectifier

With two components that can basically only go short or open, there are four possible faults: 1) Open-circuit of one of the diodes - The circuit becomes a half-wave rectifier; 2) Open-circuit of both diodes - No output voltage at all; 3) Short-circuit across one diode - The voltage from one of the secondaries appears at the output (that is, no rectification); and 4) Short circuit both diodes - No output voltage at all because the transformer's secondary is completely short-circuited.

Advantages and disadvantages

As mentioned earlier in this section, the advantage of the full-wave rectifier over the half-wave rectifier is the doubling of the pulses which makes the smoothing circuit physically smaller (for the same amount of smoothing). Compared to the bridge rectifier (discussed next), the centre-tapped transformer full-wave rectifier requires fewer diodes but this saving is more than offset by the increased cost of the centre-tapped transformer.

The bridge rectifier

The second of the full-wave rectifier circuits is the bridge rectifier. The circuit of a bridge rectifier is shown in Figure 14 below. Notice that this circuit does not need a centre-tapped transformer but has four diodes instead of two.

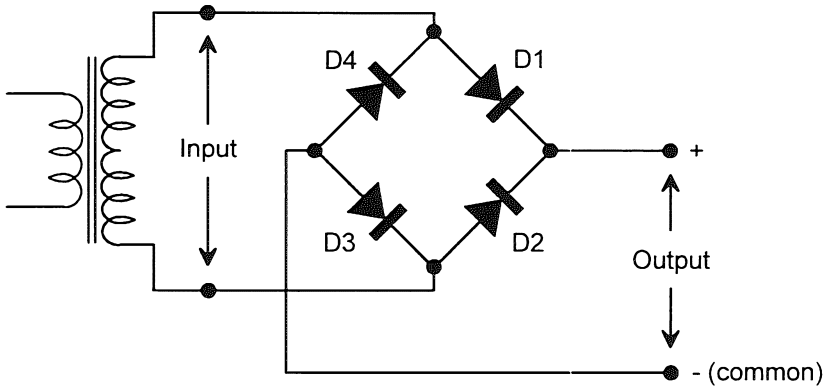


Figure 14 *A bridge rectifier connected across the output of a mains transformer*

Figure 15 below shows another way that this circuit is sometimes drawn in schematic diagrams. The diodes have been labelled so that the diodes in both circuits have the same number.

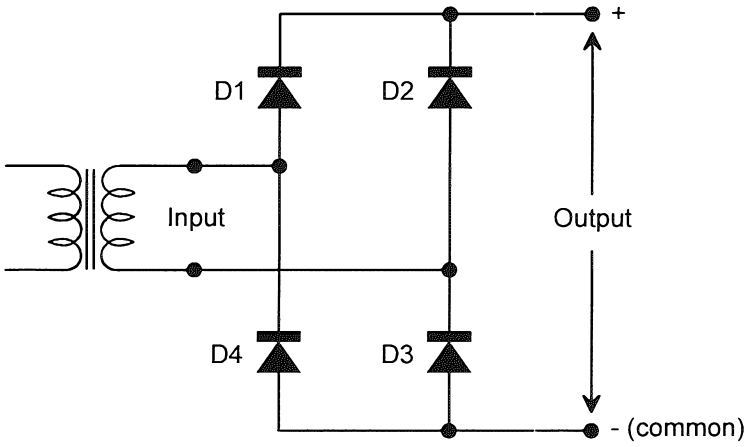


Figure 15 *The same bridge rectifier circuit as in Figure 14 drawn in a different way*

How the bridge rectifier works

To fully explain the circuit's operation, we need to redraw it showing a resistor connected across the output terminals to represent a load. This is shown in Figure 16 below.

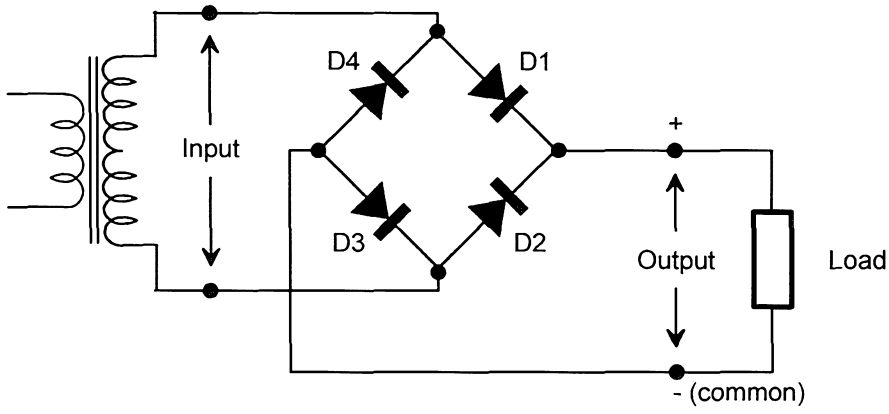


Figure 16 *The circuit of Figure 14 but with a load connected*

During the first half cycle of the secondary voltage, the anodes of *D1* and *D3* are positive with respect to their cathodes. At the same time, the cathodes of *D4* and *D2* are positive with respect to their anodes. This means that *D1* and *D3* are forward biased and conduct current but *D4* and *D2* are reverse biased and look like an open-circuit. This is shown in Figure 17 below. Importantly, the current that flows through *D1* and *D3* travels through the load (also shown in Figure 17) and develops a potential difference across it in the polarity shown.

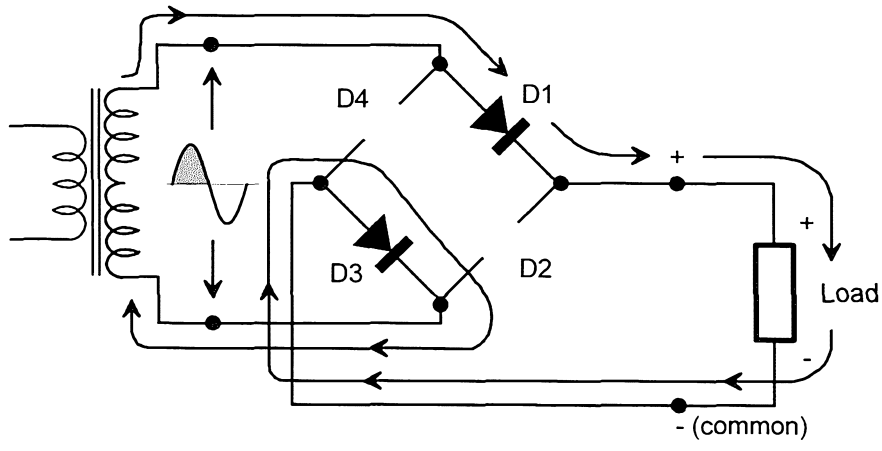


Figure 17 *The current in the circuit when the secondary voltage is positive*

During the second half cycle of the secondary voltage, the anodes of *D1* and *D3* are negative with respect to their cathodes. At the same time, the cathodes of *D4* and *D2* are negative with respect to their anodes. This means that *D1* and *D3* are reverse biased and look like an open-circuit while *D4* and *D2* are forward biased and conduct current in the direction shown in Figure 18 below. Importantly, this current travels through the load in the same direction as the current during the first half cycle, so the polarity of the potential difference across the load is also the same.

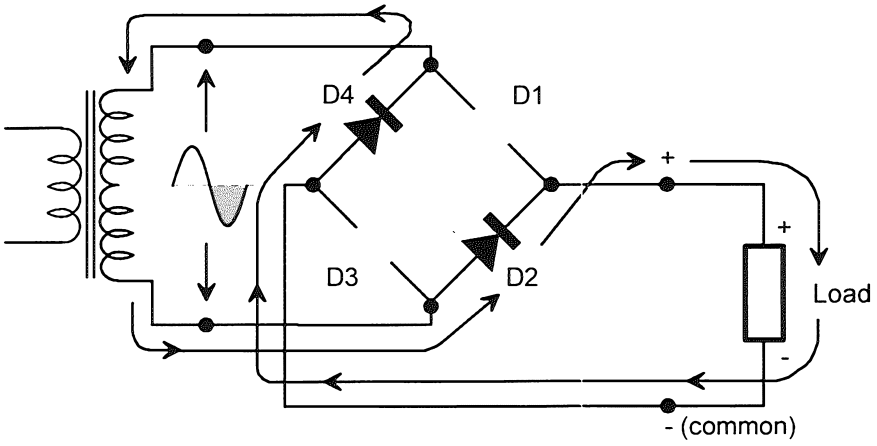


Figure 18 *The current in the circuit when the secondary voltage is negative*

Figure 19 shows the graphs for the output voltage and current (which are also the load voltage and load current) in the circuit of a bridge rectifier time-coincident with the secondary voltage.

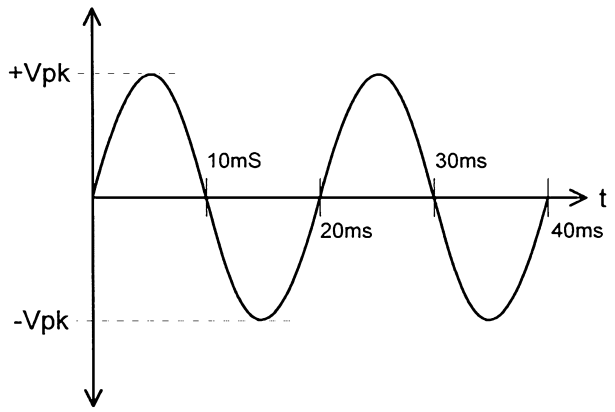


Figure 19a *The graph of the secondary voltage versus time*

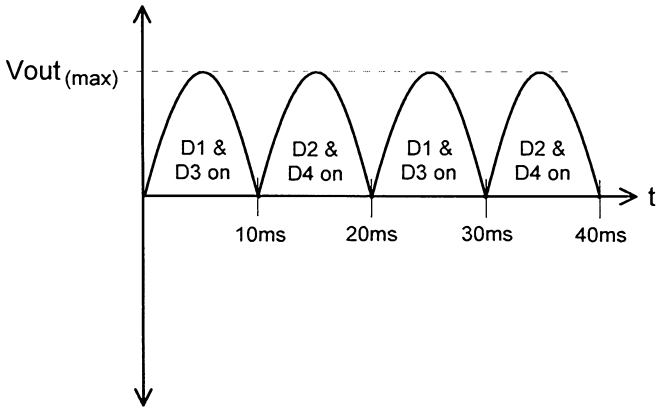


Figure 19b *The graph of output voltage (which is also the load voltage) versus time. Notice that there are twice as many pulses compared to the half-wave rectifier*

Notice also that the period of the output waveform is half the period of mains (that is, 10ms instead of 20ms)

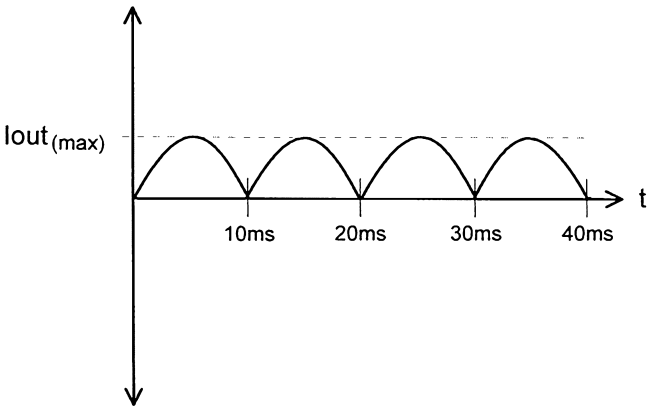


Figure 19c *The graph of circuit current (which is also the load current) versus time*

Peak inverse voltage

As just explained, the diodes in the bridge rectifier are periodically reverse biased two at a time. At the peak of the secondary voltage when the diodes are off they'll experience the peak inverse voltage (PIV). Figure 20 shows when the PIV occurs for the four diodes.

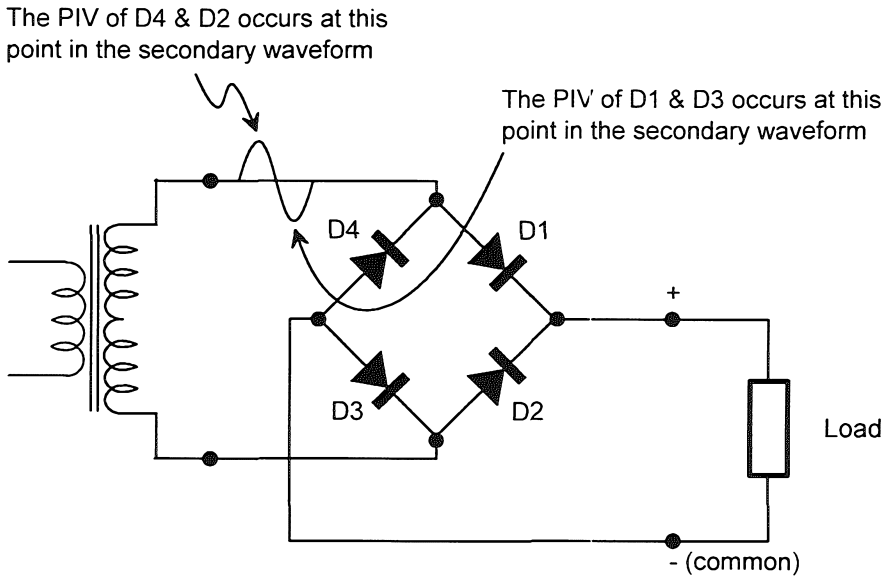

The PIV of D4 & D2 occurs at this point in the secondary waveform
The PIV of D1 & D3 occurs at this point in the secondary waveform
D4
D1
+
D3
D2
Load
- (common)

Figure 20 *The points in the secondary waveform when the diodes experience the PIV*

To understand what happens when the diodes experience their PIV lets consider just one of them - *D4*. Notice in the circuit above that the cathode of *D4* is connected to the upper output of the secondary winding. Notice also that its anode is connected to the anode of *D3*.

As the diagram in Figure 20 above shows, the diode *D4* experiences its PIV at the positive peak of the secondary waveform. At this point in time, the voltage on the cathode of *D4* is the positive peak voltage of the secondary. At the same time, the voltage on the anode of *D4* is approximately 0V. These voltages are shown in the circuit in Figure 21 (on the next page).

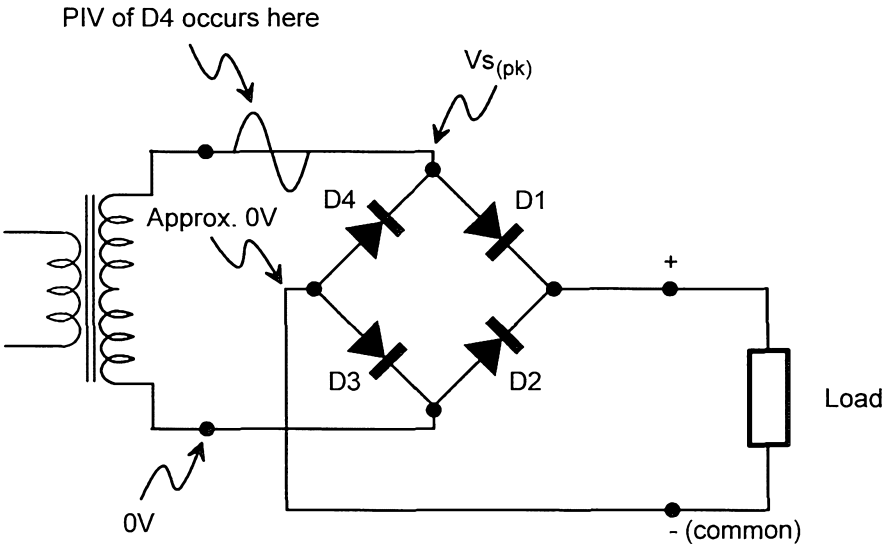


Figure 21 *The voltages around the circuit when D4 experiences its PIV*

From this diagram we can see that the potential difference across *D4* when it experiences its PIV is approximately equal to the peak secondary voltage. This is true for all of the diodes (a point not proven here).

So, we can say that for a bridge rectifier, the size of the PIV that the diodes experience is equal to:

$$PIV = Vs_{(pk)}$$

Calculating the voltages around the bridge rectifier circuit

With only one exception, all the calculations for finding the voltages and currents around a bridge rectifier are the same as for the centre-tapped transformer full-wave rectifier. The exception is the maximum output voltage ($Vout_{(max)}$). As two diodes are forward biased at any one time, the maximum output voltage is equal to:

$$Vout_{(\max)} = Vs_{(pk)} - 1.2V$$

Let's do an example.

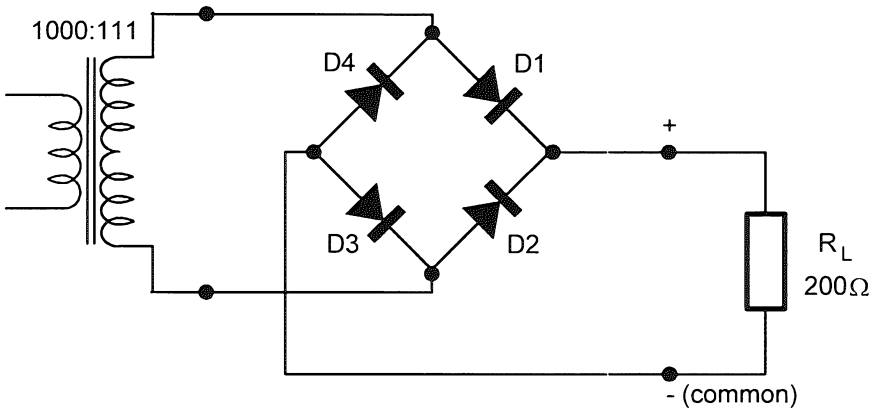


Figure 22

For the circuit in Figure 22 above we first find the peak primary voltage. As we know, mains is 240V RMS so:

$$Vp_{(pk)} = Vp \times 1.414$$

$$Vp_{(pk)} = 240V \times 1.414$$

$$Vp_{(pk)} = 339.4V$$

Next, we need to find the transformer's turns ratio for both secondaries:

$$N = \frac{N_P}{N_S}$$

$$N = \frac{1000}{111}$$

$$N = 9$$

And now we can find the transformer's secondary voltage:

$$Vs = \frac{V_P}{N}$$

$$Vs = \frac{339.4Vpk}{9}$$

$$Vs = 37.7Vpk$$

Next, find the maximum output voltage:

$$Vout_{(\max)} = Vs_{(pk)} - 1.2V$$

$$Vout_{(\max)} = 37.7Vpk - 1.2V$$

$$Vout_{(\max)} = 36.5V$$

Now we can find the average output voltage:

$$Vout_{(av)} = Vout_{(\max)} \times 0.636$$

$$Vout_{(av)} = 36.5V \times 0.636$$

$$Vout_{(av)} = 23.2V$$

And the maximum and average output currents:

$$Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$$

$$Iout_{(\max)} = \frac{36.5V}{200\Omega}$$

$$Iout_{(\max)} = 182.5mA$$

$$Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$$

$$Iout_{(av)} = \frac{23.2V}{200\Omega}$$

$$Iout_{(av)} = 116mA$$

If you compare these calculations with the calculations on pages 3-10 and 3-11 you'll notice that, all other things being equal, the bridge rectifier has slightly smaller output voltages and currents that the centre-tapped transformer full-wave rectifier.

Practise calculating the voltages and currents around a bridge rectifier by trying the following questions.

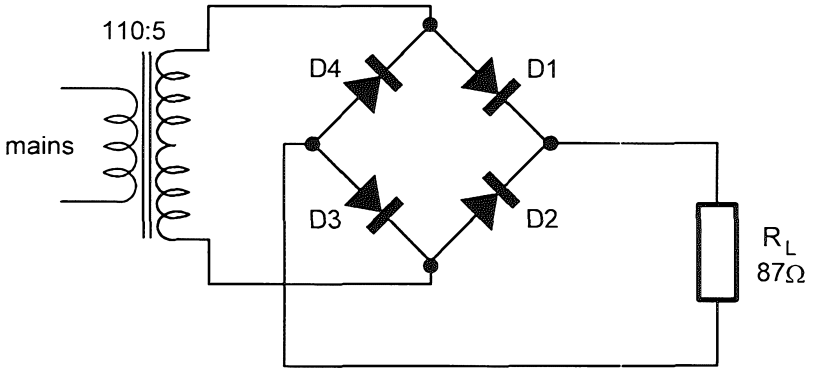


Figure 23

1. What is the peak secondary voltage (*Vs*)?

2. What is the maximum output voltage ($Vout_{(max)}$)?

3. What is the average output voltage ($Vout_{(av)}$)?

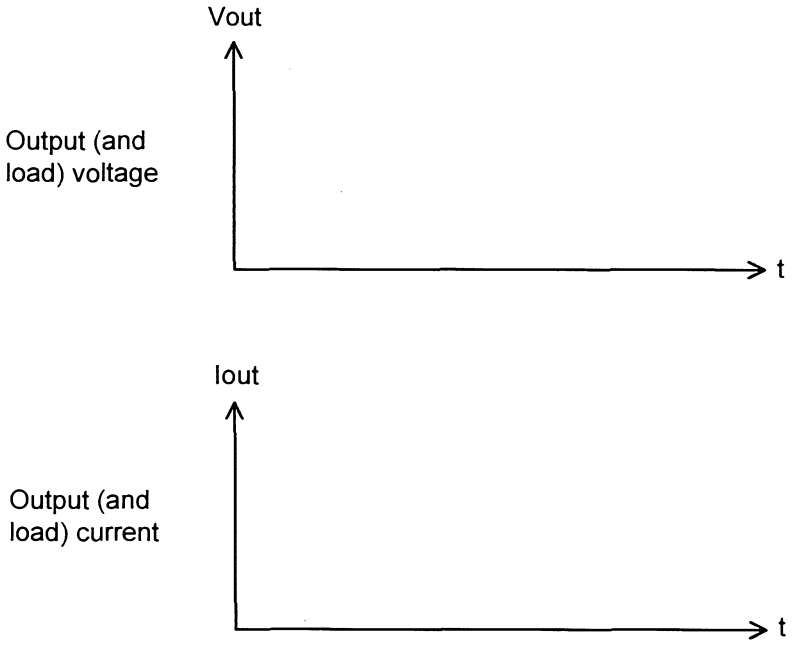
4. What is the maximum output current ($Iout_{(max)}$)?

5. What is the average output current ($Iout_{(av)}$)?

6. What is the size of the PIV that the diodes' experience?

7. What should the diodes' rated reverse breakdown voltage be?

8. In the space below, draw the voltage and current waveforms across the load. Show all voltage and time information.



Negative output voltages

The bridge rectifier that we have looked at so far provides a positive output voltage. By simply reversing the polarity of the rectifier diodes we can modify the circuit to provide a negative output voltage. This is shown in Figure 24 below.

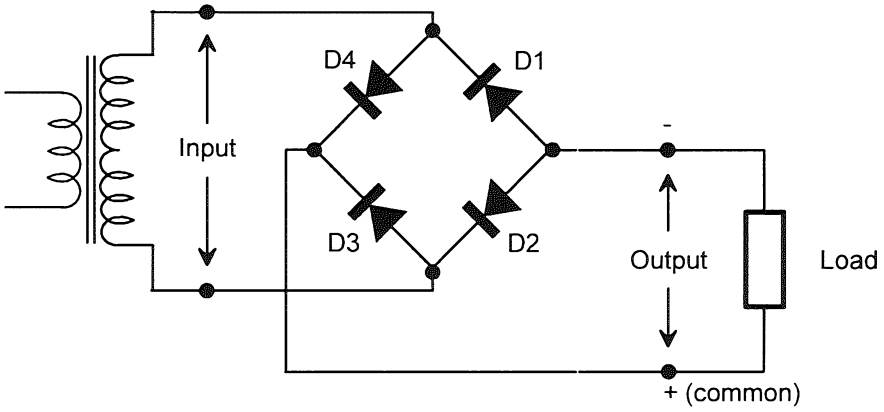


Figure 24 *A bridge rectifier circuit that provides a negative output voltage instead of a positive voltage*

The polarity of the diodes in this circuit are such that, whenever they're forward biased, current always travels up through the load from the common line. This means that the potential difference across the load is negative with respect to common.

Figure 25 below shows what the output voltage would look like if viewed on a CRO.

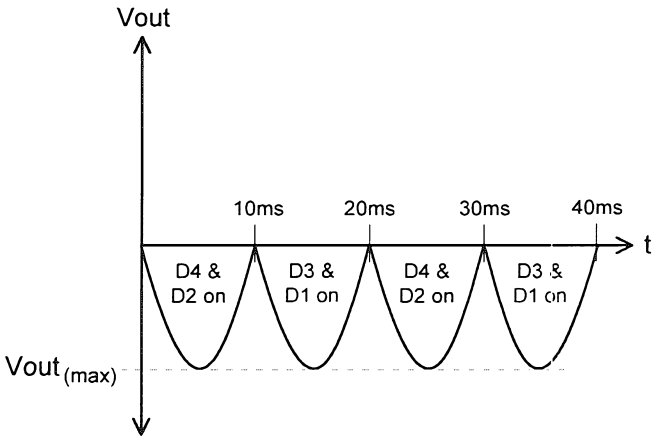


Figure 25 *The output voltage from the rectifier circuit in Figure 24*

Fault-finding the bridge rectifier

With four components each having two possible faults, there are sixteen possible fault combinations. This is too many to remember so they're not listed here. Instead, you're encouraged to think about the circuit's operation if one or more of the diodes goes short or open and the effect this would have on the output. This approach will serve you better in the long run. Practise it now. State the effect on the power supply's output for the following faults.

1) One of the diodes open-circuit:

2) One of the diodes short-circuit:

3) Two diodes (one in each path) open-circuit:

Advantages and disadvantages

As with the centre-tapped transformer full-wave rectifier, the bridge rectifier has the advantage over the half-wave rectifier that the smoothing circuitry will be physically smaller for the same amount of smoothing.

The bridge rectifier has a couple of advantages over the centre-tapped transformer full-wave rectifier also. First, they can be cheaper to make because a centre-tapped transformer is not needed. Second, as the PIV of the diodes in the bridge rectifier is smaller than the PIV of the diodes in a centre-tapped transformer full-wave rectifier, diodes with a smaller rated value of reverse breakdown voltage can be used.

There are two minor disadvantages of the bridge rectifier. First, four diodes are needed instead of two but this is not really a problem because rectifier diodes for the power supplies of electronics equipment are very cheap. Second, the maximum output voltage is 1.2V less than the peak secondary voltage instead of 0.6V less. This is not really a problem either as a transformer with a higher secondary voltage can simply be used to compensate for the extra loss.

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Student notes

Skill practice 3

Practise measuring diode operating conditions in full-wave rectifier circuits (both functional and faulty) using a DMM and an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¾ hours to complete this exercise.

Equipment

- 15V AC power supply
- prototyping panel
- two DMMs (but only one set of meter leads)
- four 1N4004 diodes
- 150Ω 5W resistor
- two BNC to alligator-clip leads
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the dual 15V AC power supply to simulate a centre-tapped transformer as shown in Figure 1 below.

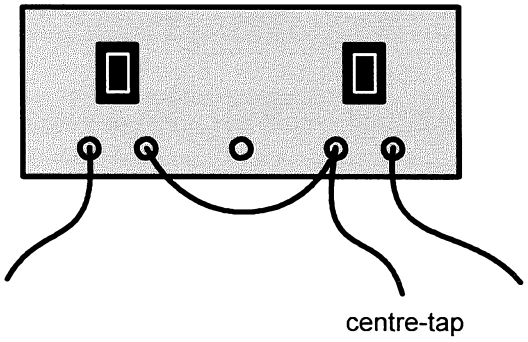


Figure 1

4. Wire the circuit of Figure 2 on the breadboard. Ensure that the transformer's centre-tap is connected to the earth terminal on the AC power supply.

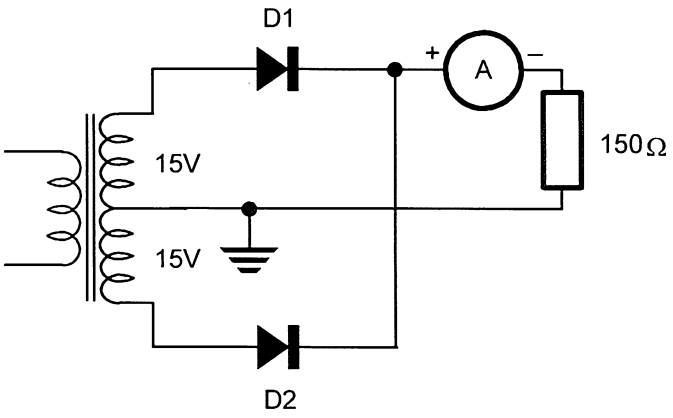


Figure 2

5. Turn on the AC power supply and use the DMM to measure the potential difference across either one of the transformer's secondaries. Record your measurement in Table 1 below.

   Note: The voltage will higher than 15V indicated in Figure 2 but that's ok.

6. Use the **measured** secondary voltage to calculate and record the peak secondary voltage.

7. Use the peak secondary voltage to calculate and record the rectifier's maximum output voltage $Vout_{(max)}$.

8. Use the $Vout_{(max)}$ to calculate and record the rectifier's average output voltage ($Vout_{(av)}$).

9. Use the $Vout_{(av)}$ to calculate and record the rectifier's average output current ($Iout_{(av)}$).

Table 1

Measured secondary voltage (RMS)	
Calculated secondary voltage (peak)	
Calculated $Vout_{(max)}$	
Calculated $Vout_{(av)}$	
Calculated $Iout_{(av)}$	

10. Turn off the AC power supply.

11. Connect the CRO's channel 1 input across the load resistor (connect the black alligator clip of the CRO lead to the circuit common/earth).

12. Set the CRO's channel 1 vertical attenuation control to the *5V/div* position.

13. Set the CRO's channel 1 input coupling control to the *GND* position.

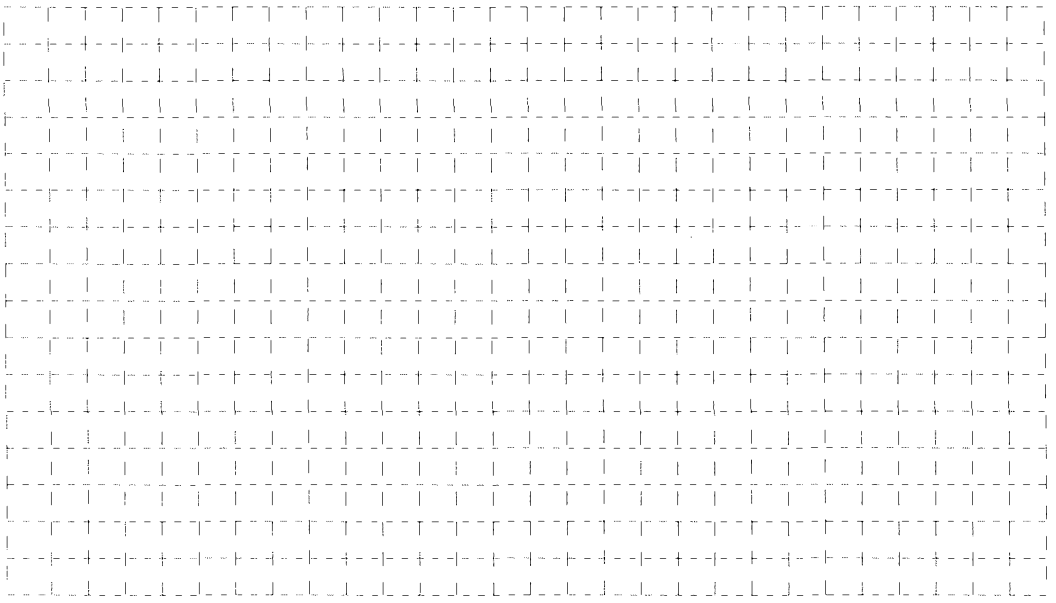
14. Move the CRO's trace so that it's aligned with the horizontal line that's second from the bottom of the graticule.

    Note: Once you've done this, you'll know where zero volts is on the graticule so don't move the trace's vertical position after performing this step.

15. Set the CRO's channel 1 input coupling control to the *DC* position.

16. Turn on the AC power supply.

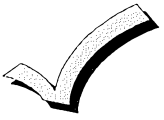
17. Draw the voltage across the load on the graph below.



18. Indicate on your drawing which diode could be conducting during each half cycle of the potential difference across the load.

19. Use the CRO to measure as accurately as possible the rectifier's maximum output voltage $Vout_{(max)}$ and show this on your drawing above.

20. Use the CRO to measure the waveform's period and show this on your drawing above.



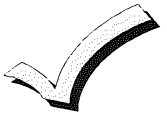
The teacher needs to check your work at this point...

Question 1
In what way is the waveshape of the potential difference across the load for this circuit different to the waveshape across the load of a half-wave rectifier?

Question 2
Is the voltage across the load resistor AC or DC? Explain your answer.

Question 3
How do your calculated and measured values of $Vout_{(max)}$ compare? Explain any differences.

Question 4
Use the load waveform's measured period to calculate its frequency.



The teacher needs to check your work at this point...

21. Use the DMM to measure the load current. Record your measurement in the appropriate space in Table 2 below.

22. Disconnect the DMM and use it to measure and record the potential difference across the load.

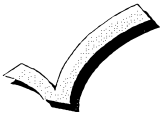
Table 2

Measured load voltage	
Measured load current	

Question 5
What type of voltage and current have the DMMs measured?

- ☐ Peak-to-Peak
- ☐ Average
- ☐ RMS
- ☐ Peak

Question 6
Compare the theoretical values (Table 1) and measured values (Table 2) of potential difference and current. Are they the same? What might cause any differences?



The teacher needs to check your work at this point...

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23. Turn off the AC power supply.

24. Disconnect one of the legs of any one of the diodes (but not both) from the circuit. This simulates an open-circuit for that diode.

25. Turn on the power supply.

26. Observe the potential difference across the resistor on the CRO.

27. Also note the change in load current.

Question 7
What happens to the potential difference across the load when one of the diodes is an open-circuit and why does this happen?

_____

_____

_____

Question 8
What happens to the current through the load when one of the diodes is an open-circuit and why does this happen?

_____

_____

_____

The teacher needs to check your work at this point...

28. Dismantle the circuit then wire the circuit in Figure 3. Use only one of the 15V AC power supply's outputs for the transformer in the circuit.

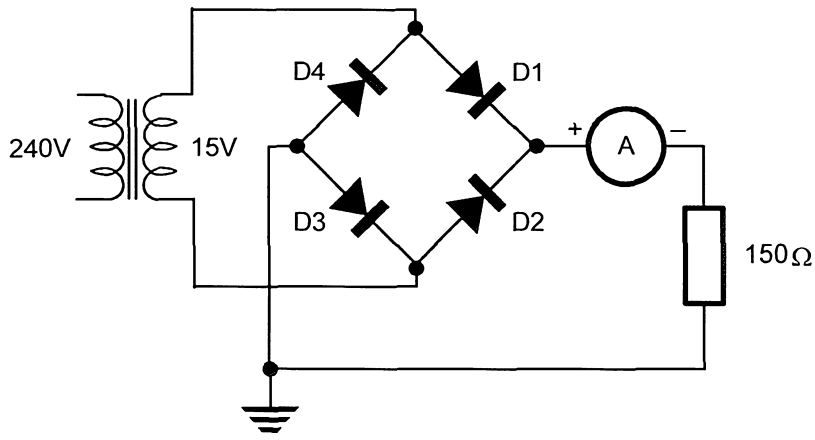


Figure 3

29. Connect the CRO's channel 1 input across the load resistor.

30. Check that the input coupling of channel 1 is still set to the *DC* position.

31. Turn on the power supply and use the CRO to look at the potential difference across the load resistor

32. Draw the load voltage on the graph below.

33. Find where the 0V line occurs on the waveform and show this on your drawing.

34. Indicate on your drawing which diodes could be conducting during each half cycle of the potential difference across the load.

35. Use the CRO to measure as accurately as possible the rectifier's maximum output voltage $Vout_{(max)}$ and show this on your drawing.

36. Use the CRO to measure the waveform's period and show this on your drawing.

37. Measure the potential difference across the load using the DMM. Record your measurement in Table 3 below.

38. Use the ammeter to measure and record the current through the load.

Table 3

Measured load voltage	
Measured load current	

Question 9

Why is the potential difference across the load of a bridge rectifier smaller than the potential difference across the load of the full-wave rectifier of Figure 1 (see Table 2)?

39. Turn off the AC power supply.

40. Disconnect one of the legs of any one of the diodes from the circuit. This simulates an open-circuit for that diode.

41. Turn on the power supply.

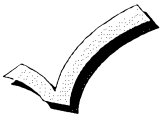
42. Observe the potential difference across the resistor on the CRO.

43. Also note the change in load current.

Question 10
What happens to the potential difference across the load when one of the diodes is an open-circuit and why does this happen?

Question 11
What happens to the current through the load when one of the diodes is an open-circuit and why does this happen?

Question 12
Is it possible for there to still be a load voltage and current if two diodes in the bridge rectifier go open circuit? Explain your answer.



The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 12 refer to the circuit of Figure 1 below.

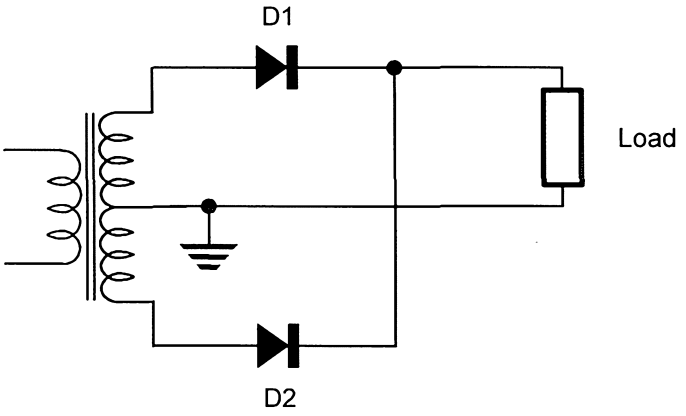

Figure 1

1. Name the circuit.

_____

2. What type of voltage is developed across the load?

   ☐ Positive voltage DC
   ☐ Positive voltage AC
   ☐ Negative voltage DC
   ☐ Negative voltage AC

3. Draw on the schematic diagram the direction of current around the circuit during the positive half-cycle of the secondary voltage.

4. Show the polarity of the potential difference across the diodes and load during the positive half-cycle of the secondary voltage.

5. Draw on the schematic diagram the direction of current around the circuit during the negative half-cycle of the secondary voltage. [Tip: Use a different coloured pen to the one you used for question 3.]

6. Show the polarity of the potential difference across the diodes and load during the negative half-cycle of the secondary voltage.

7. Draw the waveforms of the secondary voltage and the potential difference across the resistor time coincident with each other. Show all time information.

8. What is the frequency of the pulsating DC across the load?

_____

9. Indicate on your drawing above which diode is conducting during each half-cycle of the potential difference across the load.

10. What would happen to the waveshape of the potential difference across the load if *D1* went open-circuit?

_____

_____

11. What would happen to the average potential difference across the load if *D1* went open-circuit?

_____

12. What serious problem would occur if *D2* went short-circuit?

_____

13. Redraw the circuit of Figure 1 so that it produces a negative output voltage instead of a positive output voltage.

14. Draw on your schematic diagram the direction of current around the circuit during the positive half-cycle of the secondary voltage.

15. Show the polarity of the potential difference across the diodes and load during the positive half-cycle of the secondary voltage.

16. Draw on your schematic diagram the direction of current around the circuit during the negative half-cycle of the secondary voltage.

17. Show the polarity of the potential difference across the diodes and load during the negative half-cycle of the secondary voltage.

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Questions 18 to 25 refer to the circuit of Figure 2

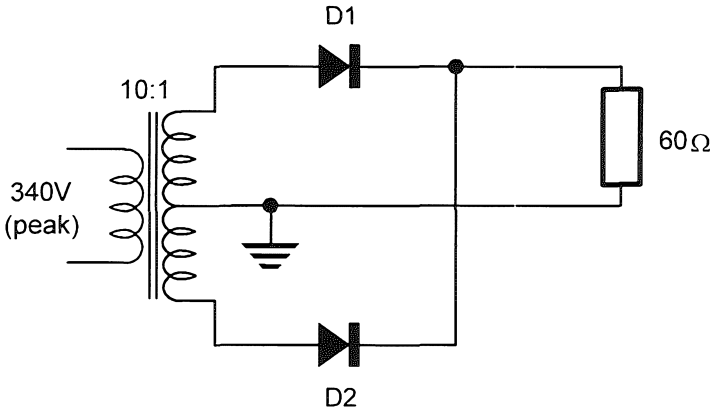

Figure 2

18. What is the maximum potential difference across the resistor ($Vout_{(max)}$)?

19. What is the average potential difference across the resistor ($Vout_{(av)}$)?

20. What is the maximum current through the resistor ($Iout_{(max)}$)?

21. What is the average current through the resistor ($Iout_{(av)}$)?

22. What is the *peak inverse voltage* across the diodes?

23. What rated value of *reverse breakdown voltage* should the diodes have?

24. The peak inverse voltage across *D1* occurs at the peak of

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

25. The peak inverse voltage across *D2* occurs at the peak of

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

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26. What is the advantage of the centre-tapped transformer full-wave rectifier over the half-wave rectifier?

_____

_____

27. What is the disadvantage of the centre-tapped transformer full-wave rectifier over the half-wave rectifier?

_____

_____

Questions 28 to 38 refer to the circuit of Figure 3

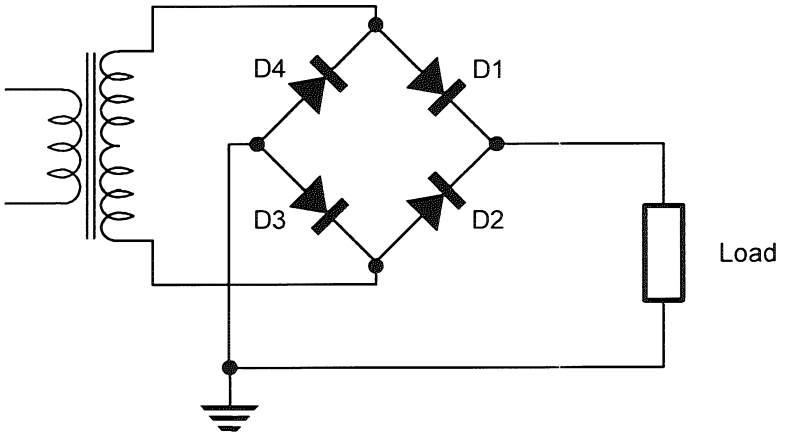


Figure 3

28. Name the circuit.

_____

29. What type of voltage is developed across the load?

- ☐ Positive voltage DC
- ☐ Positive voltage AC
- ☐ Negative voltage DC
- ☐ Negative voltage AC

30. Draw on the schematic diagram the direction of current around the circuit during the positive half-cycle of the secondary voltage.

31. Show the polarity of the potential difference across the diodes and load during the positive half-cycle of the secondary voltage.

32. Draw on the schematic diagram the direction of current around the circuit during the negative half-cycle of the secondary voltage.

33. Show the polarity of the potential difference across the diodes and load during the negative half-cycle of the secondary voltage.

34. Draw the waveforms of the secondary voltage and the potential difference across the resistor time coincident with each other. Show all time information.

35. Indicate on your drawing above which diodes are conducting during each half-cycle of the potential difference across the load.

36. What would happen to the waveshape of the potential difference across the load if *D1* went open-circuit?

37. What would happen to the average potential difference across the load if *D1* went open-circuit?

38. What serious problem would occur if *D2* went short-circuit?

39. Redraw the circuit of Figure 3 so that it produces a negative output voltage instead of a positive output voltage.

40. Draw on your schematic diagram the direction of current around the circuit during the positive half-cycle of the secondary voltage.

41. Show the polarity of the potential difference across the diodes and load during the positive half-cycle of the secondary voltage.

42. Draw on your schematic diagram the direction of current around the circuit during the negative half-cycle of the secondary voltage.

43. Show the polarity of the potential difference across the diodes and load during the negative half-cycle of the secondary voltage.

Questions 44 to 50 refer to the circuit of Figure 4

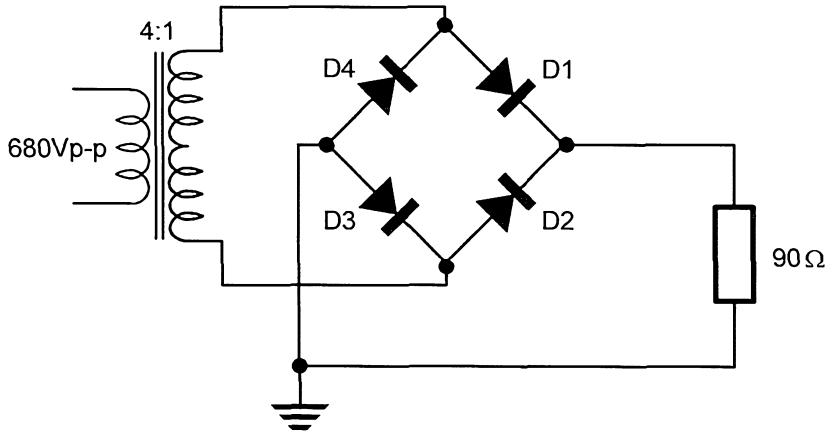


Figure 4

44. What is the maximum potential difference across the resistor ($Vout_{(max)}$)?

45. What is the average potential difference across the resistor ($Vout_{(av)}$)?

46. What is the maximum current through the resistor ($Iout_{(max)}$)?

47. What is the average current through the resistor ($Iout_{(av)}$)?

48. What is the *peak inverse voltage* across the diodes?

49. The peak inverse voltage across *D1* occurs at the peak of

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

50. The peak inverse voltage across *D2* occurs at the peak of

- ☐ the positive half-cycle of the secondary voltage.
- ☐ the negative half-cycle of the secondary voltage.
- ☐ both half-cycles of the secondary voltage.

51. What is the advantage of the bridge rectifier over the half-wave rectifier?

52. What are two advantages of the bridge rectifier over the centre-tapped transformer full-wave rectifier?

Student notes

Section 4 Filtering (smoothing)

Purpose To develop your ability to use test equipment to test filtered rectifier circuits, recognise when the circuit is faulty, and identify the likely faulty component.

Objectives At the end of this section you should be able to:

- Show where a *filter capacitor* is connected in the circuit of a half-wave and full-wave rectifier power supply
- State the type of capacitor usually used for a filter capacitor
- Show the correct polarity for connecting a filter capacitor
- State the reason for a filter capacitor
- Explain how a filter capacitor smooths the pulsating DC of a rectifier output
- Define the terms *ripple voltage*, *ripple frequency* and *effective DC voltage*
- State the ideal effective DC and ripple voltages for a filtered rectifier
- Calculate the effective DC voltage of a filtered rectifier given the maximum output voltage and the amplitude of the ripple voltage
- State the ripple frequency of half-wave and full-wave rectifiers
- Calculate the *ripple factor* given the effective DC and ripple voltages
- State the ideal ripple factor for a filtered rectifier
- List the factors that affect the effective DC and ripple voltages
- Use a DMM and oscilloscope to perform measurements of key potential differences in filtered half-wave rectifier and filtered full-wave rectifier circuitss

Introduction

The last two sections introduced you to the half-wave rectifier circuit and the two full-wave rectifier circuits. As you have seen, the output of these circuits is less than ideal in that they produce a pulsating DC voltage per Figures 1a and 1b below.

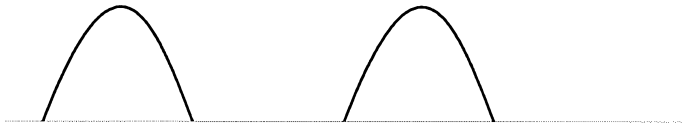


Figure 1a
The pulsating DC out of a half-wave rectifier

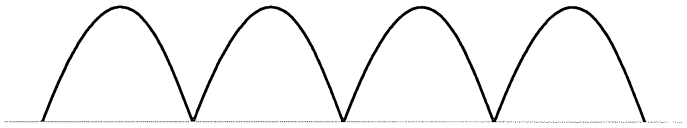


Figure 1b
The pulsating DC out of a full-wave rectifier

The reason these pulsating DC outputs are not considered to be ideal is because the DC is changing. Electronics circuits need the supply to be a steady DC voltage to work well. In this section we'll learn about a fairly simple modification to rectifier circuits that "smooth" their pulsating DC outputs.

Smoothing a pulsating DC

Changing the output of a rectifier circuit from a pulsating DC voltage to a steady DC voltage requires the simple addition of a capacitor connected directly across the rectifier's output (see Figure 2 below). For reasons that will be explained later in this section the capacitor is usually called a *filter capacitor*.

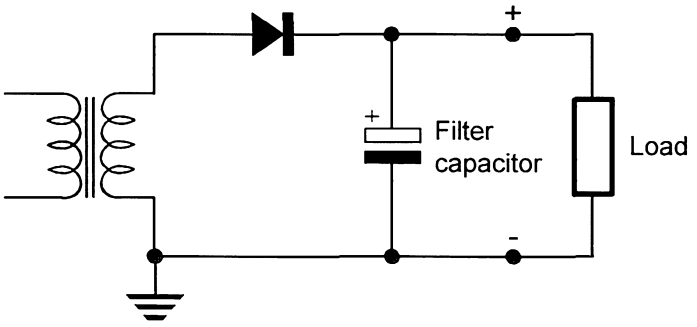


Figure 2

The addition of a filter capacitor to the circuit in this way improves the output voltage dramatically as demonstrated using a half-wave rectifier in Figures 3a and 3b below.

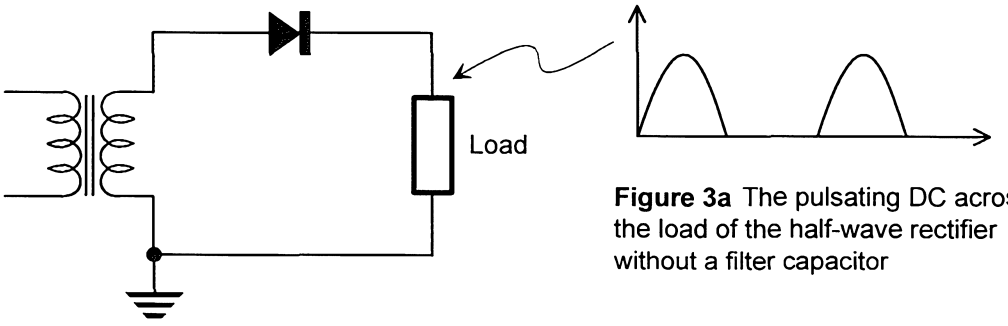


Figure 3a The pulsating DC across the load of the half-wave rectifier without a filter capacitor

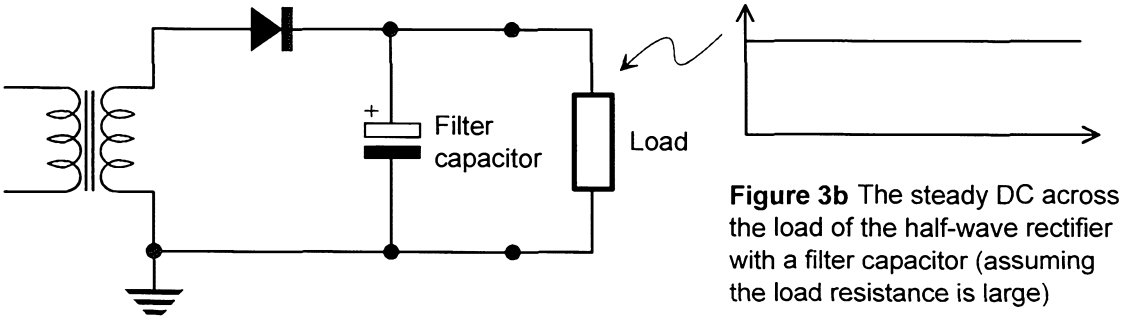


Figure 3b The steady DC across the load of the half-wave rectifier with a filter capacitor (assuming the load resistance is large)

The same technique is used to smooth the output of the two full-wave rectifier circuits and examples are shown in Figures 4 and 5.

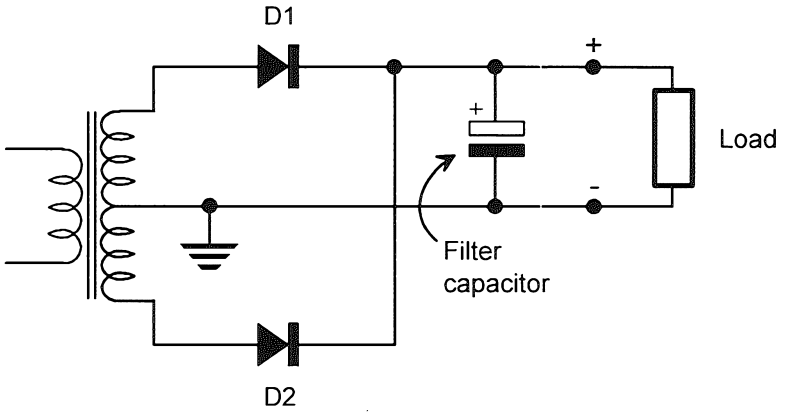


Figure 4 *The full-wave rectifier with filter capacitor*

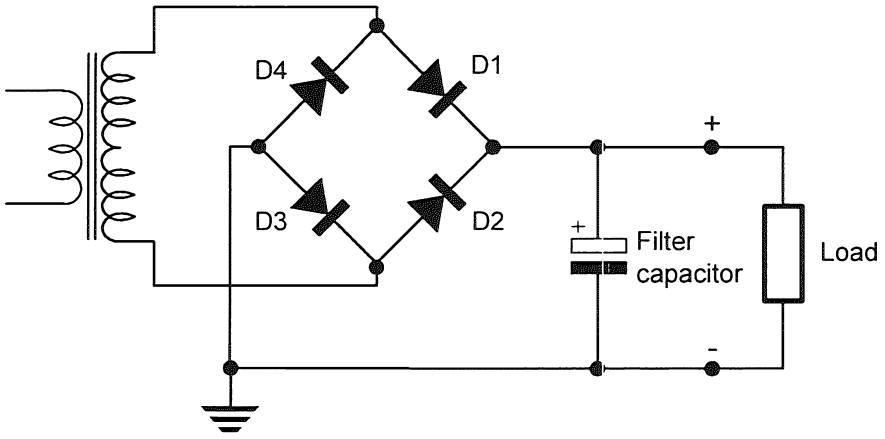


Figure 5 *The bridge rectifier with filter capacitor*

For reasons that will be explained later in this section, the filter capacitor needs to have a fairly large value of capacitance - typically in the thousands of micro Farads. As such, electrolytic capacitors are used (usually the aluminium electrolytic type).

As you know, electrolytic caps are polarised and so they must be connected in the circuit in the same polarity as the potential difference across it (see Figures 2, 4 and 5). If electrolytic capacitors are connected in the wrong polarity they may explode. As a service technician you must take care to put capacitors in the correct polarity when replacing them.

How does the filter capacitor work?

To understand how the filter capacitor smooths the pulsating DC, let's first consider the unloaded half-wave rectifier in Figure 6 below.

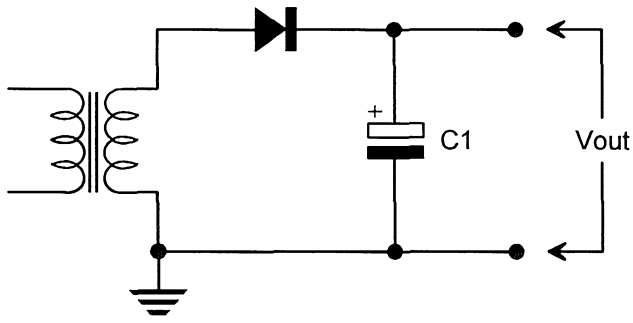


Figure 6 *An unloaded half-wave rectifier with filter capacitor*

After the circuit is first turned on, current flows in the loop (as shown in Figure 7) during the first positive half-cycle of the secondary voltage because the diode is initially forward biased.

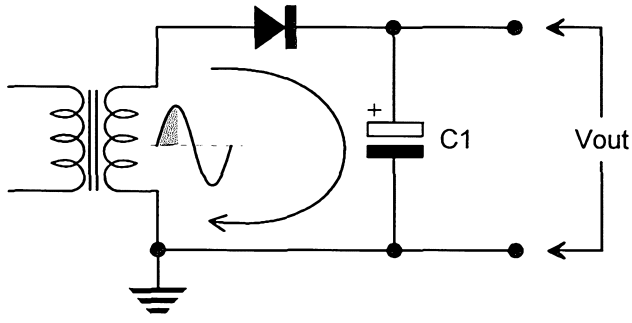


Figure 7 *Current flows around the circuit during the first positive half-cycle of the secondary voltage*

With no resistance in the loop, there is no time delay in the charging of the capacitor and so the potential difference across it is the same as the secondary voltage minus 0.6V (for the forward bias voltage drop across the diode). When the secondary voltage reaches the first positive peak, the potential difference across the capacitor is equal to the maximum output voltage (that is, $Vout_{(\max)} = Vs_{(pk)} - 0.6V$).

At this point, something interesting happens. As the secondary voltage begins to head back toward 0V, the potential difference across the capacitor isn't allowed to drop. To explain, for the potential difference across the capacitor to drop, its stored charge must be discharged. But, this can't happen because current would have to flow in the opposite direction to the charging current but the diode blocks current in the reverse direction. So, the potential difference across the capacitor gets "stuck" at the maximum output voltage ($Vout_{(max)}$). This is all shown in Figure 8 below in a graph of potential difference across the capacitor (shown time coincident with the secondary voltage).

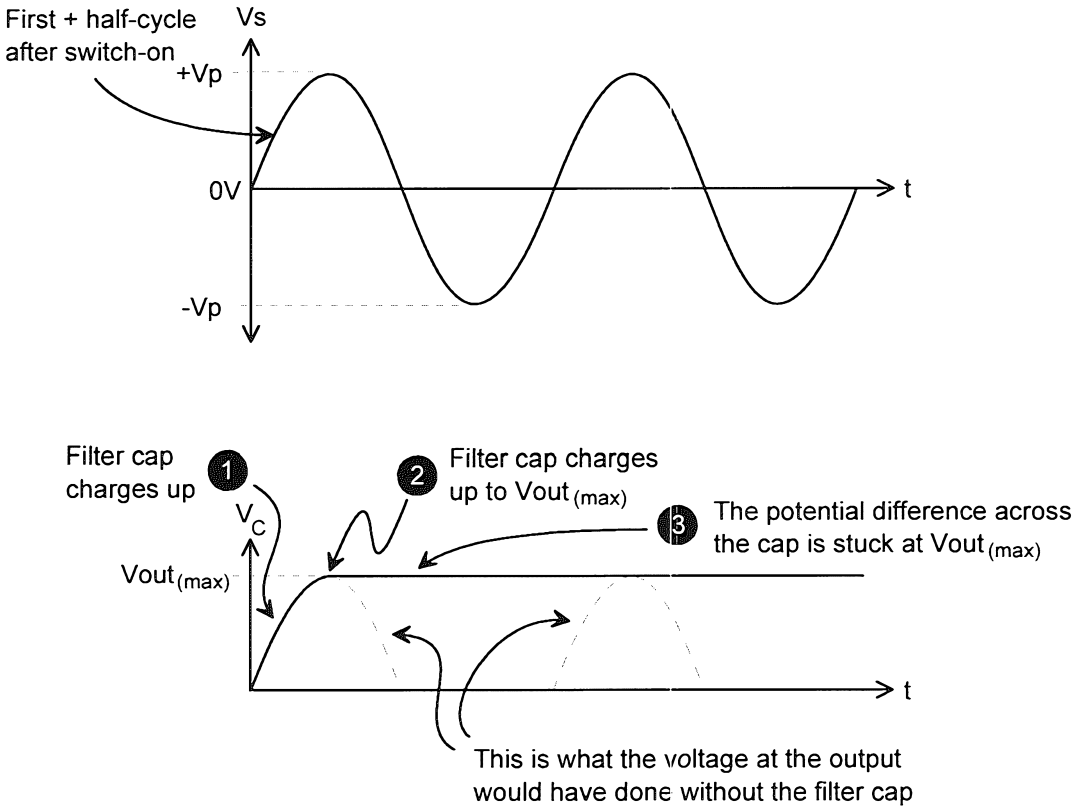


Figure 8 *The potential difference of across the capacitor shown time coincident with the secondary voltage*

As you can see from the graph, once the secondary voltage reaches its first positive peak the filter capacitor stays at the maximum output voltage ($Vout_{(max)}$) producing a steady state DC voltage out of the circuit.

Importantly, current doesn't flow through the diode during the entire positive half-cycle of the secondary voltage as it does in the half-wave rectifier without a filter capacitor.

To explain, because the potential difference across the capacitor gets stuck at the maximum output voltage ($Vout_{(max)}$), the voltage on the diode's cathode is also stuck at $Vout_{(max)}$. The moment the secondary voltage reaches the first positive peak and begins to drop the potential difference across the diode is no-longer the required 0.6V needed to turn it on. So it turns off. Moreover, as the secondary voltage continues to head toward 0V and drops below $Vout_{(max)}$ the diode actually becomes reverse biased.

This means that the diode only conducts during the first half of the first positive half-cycle of the secondary voltage in this circuit. This is shown in the graphs in Figure 9 below.

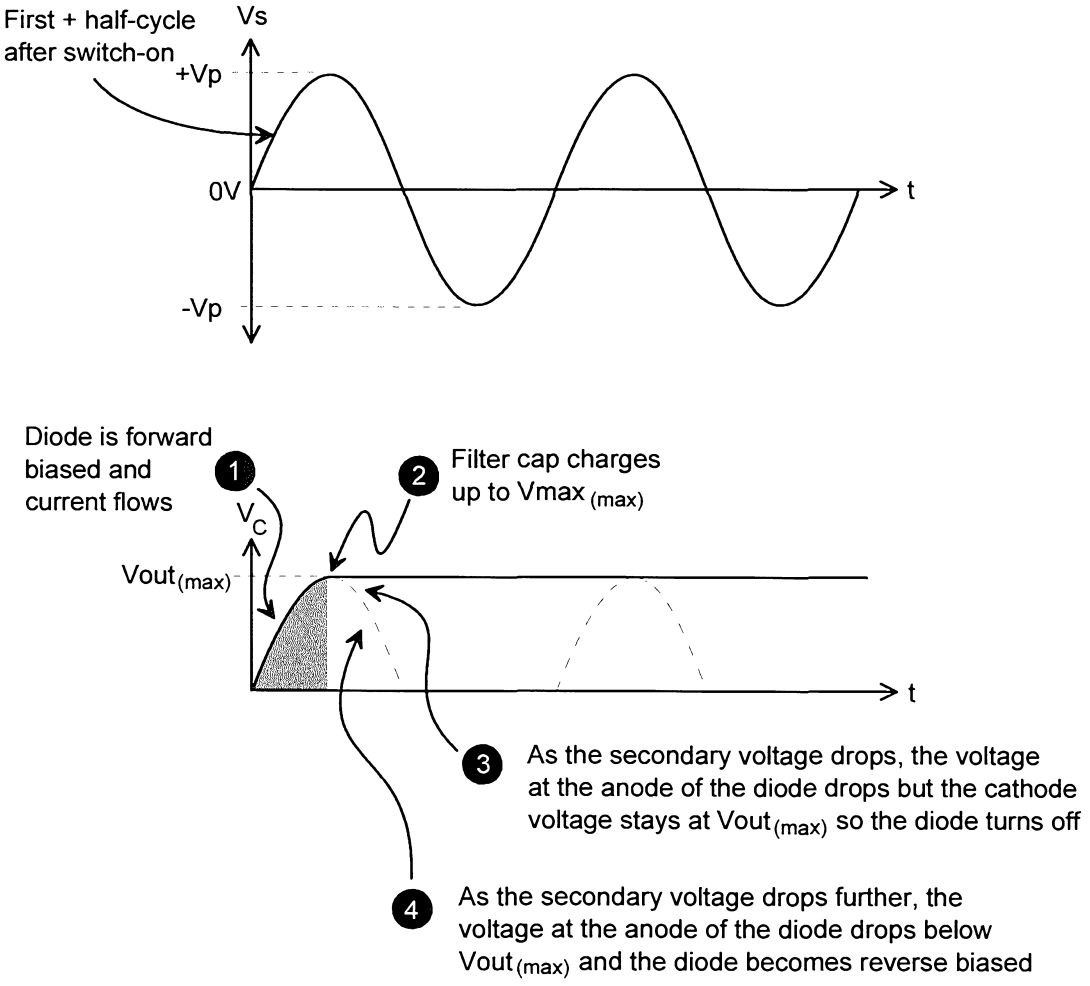

First + half-cycle after switch-on
Vs
+Vp
0V
t
-Vp
Diode is forward biased and current flows
1
2
Filter cap charges up to Vmax (max)
Vc
Vout(max)
t
3
As the secondary voltage drops, the voltage at the anode of the diode drops but the cathode voltage stays at Vout(max) so the diode turns off
4
As the secondary voltage drops further, the voltage at the anode of the diode drops below Vout(max) and the diode becomes reverse biased

Figure 9 *The diode only conducts during the shaded region in the graph of V_C versus time*

At this point, you might be tempted to think that once the filter capacitor has charged up, we don't need the transformer and rectifier any more. However, in practice this is not the case as you will see.

The effect of a load on the output

As just explained, connecting a filter capacitor across the output of an unloaded rectifier produces a constant output voltage. This is also true for a loaded power supply when two conditions are met: a) the load resistance is very large; and b) the filter capacitor's value is very large.

In practice however, these two conditions are not always satisfied and so the smoothing effect isn't perfect. To explain, consider the loaded rectifier in Figure 10 below. When the circuit is first turned on, current flows around the circuit via both the capacitor and the load during the first half of the first positive half-cycle of the secondary voltage.

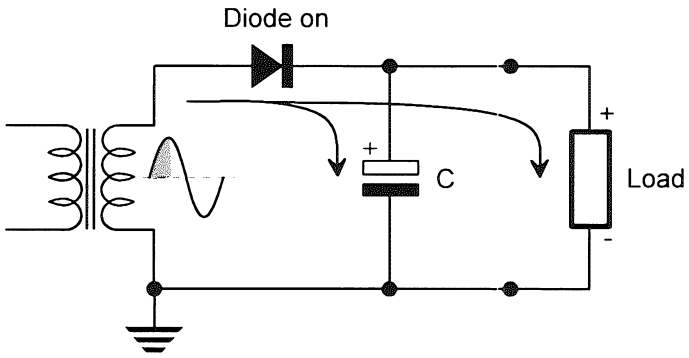


Figure 10 *Current in the circuit of a half-wave rectifier with filter capacitor during the first half of the first positive half-cycle of the secondary voltage*

Once the secondary voltage reaches the peak and begins to head back toward 0V the diode turns off. With the diode turned off, the circuit just looks like a resistor connected across a capacitor. So, the capacitor begins to discharge itself into the load (see Figure 11).

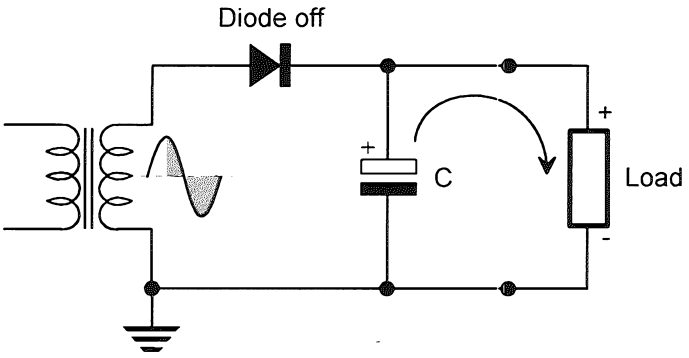


Figure 11 *The current in the circuit after the secondary voltage has reached the peak of its first positive half-cycle*

Because the capacitor's stored charge discharges via the load, the potential difference across it (and hence the potential difference across the load) begins to drop. However, the capacitor's charge gets "topped-up" during the next positive half-cycle of the secondary voltage once it exceeds the potential difference across the capacitor. This is shown in graph form in Figure 12.

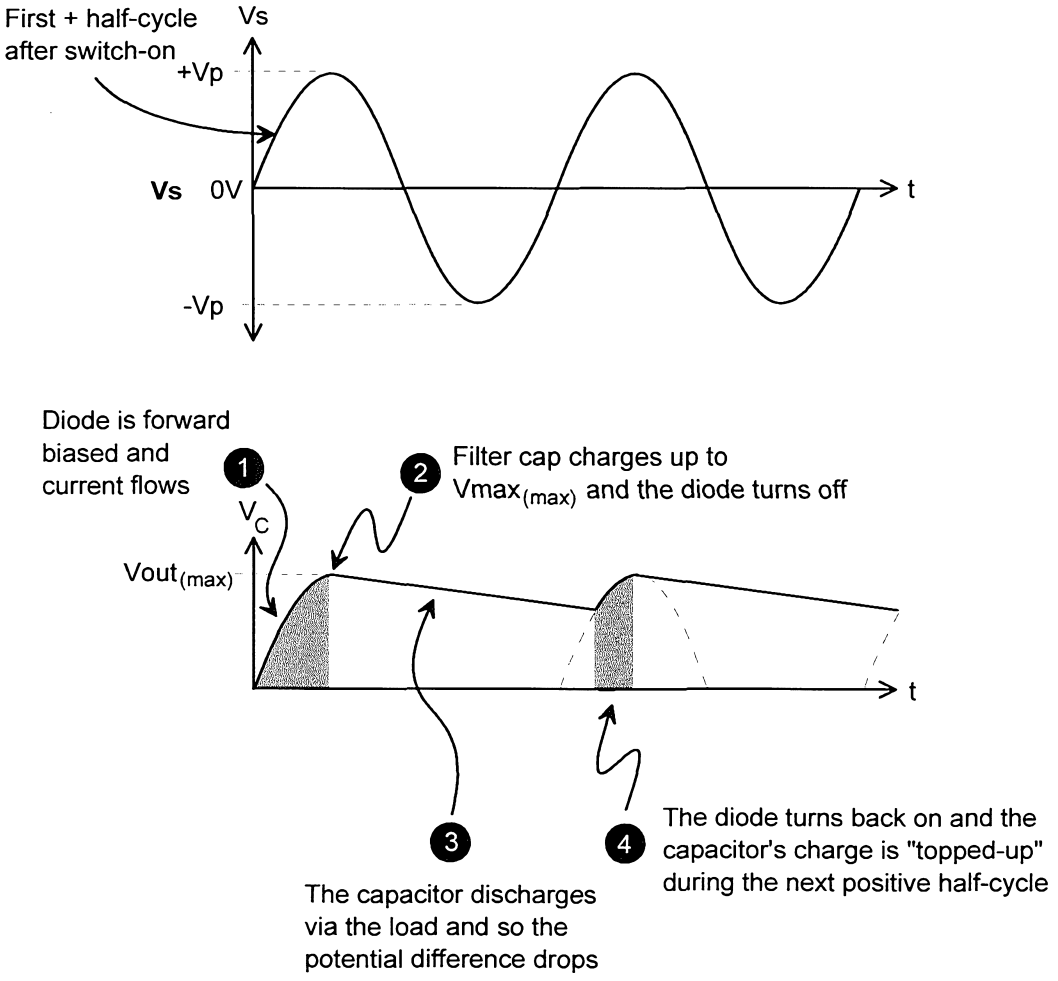


Figure 12 *The potential difference across the capacitor and the load time coincident with the secondary voltage*

So, for circuits in which the load can drain the charge on the filter capacitor, the output voltage is no-longer perfectly flat. Instead, the DC voltage moves up and down as though it has a "ripple" on it.

Ripple voltage and effective DC voltage

The fact that the filter capacitor always discharges itself into the load when the rectifier diodes are reverse biased gives us a couple of power supply characteristics that we need to learn about because they're used to compare between different power supplies.

The first characteristic is *output ripple voltage* ($Vout_{(ripple)}$) and this is the peak-to-peak voltage of the variation of the loaded DC output voltage of a filtered rectifier circuit (see Figure 13).

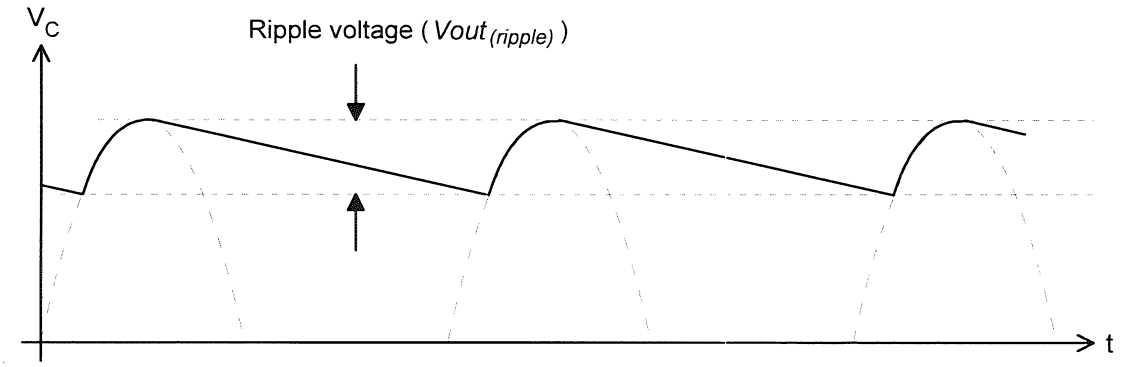
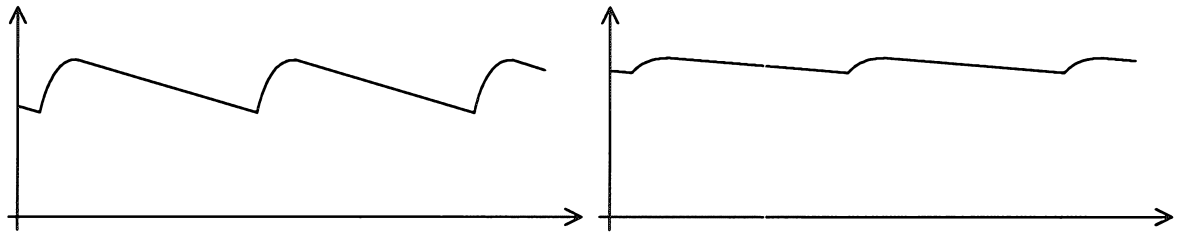


Figure 13 *The output ripple voltage is the peak-to-peak voltage of the variation of the DC output*

The smaller the size of the ripple voltage, the more smooth the DC output voltage and therefore the better the power supply (see Figures 14a & 14b).



14a Relatively large ripple - not so good

14b The smaller the ripple the better

The ideal amount of ripple voltage is 0V but this is theoretically impossible to achieve for loaded unregulated power supplies. [Though, it can be reduced to a level too small to measure with a CRO!]

The second characteristic of DC power supplies is the *effective DC output voltage* ($Vout_{(DC)}$) which is the voltage that a voltmeter would measure.

The effective DC output voltage is the average voltage across the load. Graphically, the effective DC output voltage is half way between the peaks of the output ripple voltage and this is shown in Figure 15 below.

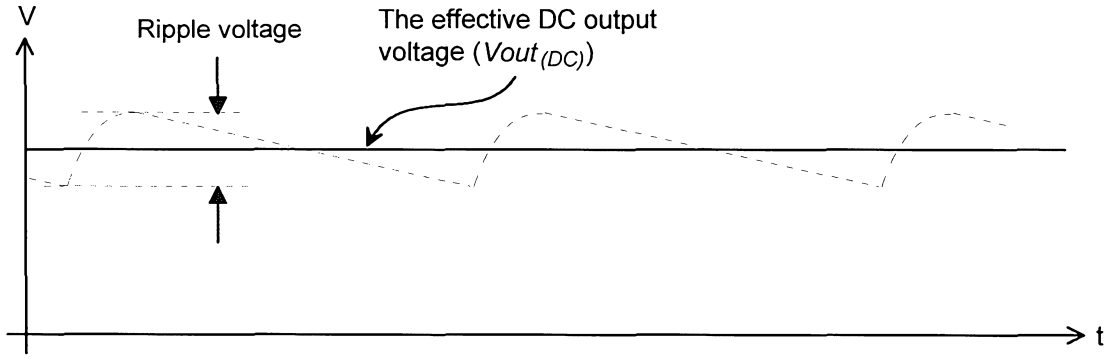
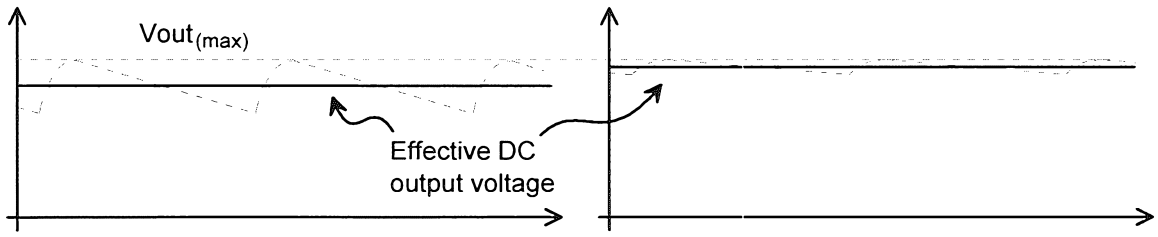


Figure 15 *The effective DC voltage is half way between the peaks of the ripple voltage*

The effective DC output voltage can be calculated if the maximum output voltage ($Vout_{(max)}$) and the peak-to-peak value of the output ripple voltage ($Vout_{(ripple)}$) are known using the equation:

$$Vout_{(DC)} = Vout_{(\max)} - \left(\frac{Vout_{(ripple)(p-p)}}{2}\right)$$

Not surprisingly, the smaller the output ripple voltage for a given maximum voltage, the bigger the effective DC output voltage (see Figure 16). For any circuit, the highest DC output voltage occurs when the ripple voltage is 0V. In which case, the effective output DC voltage is the same as the maximum output voltage ($Vout_{(max)}$).



16a A relatively large ripple gives a lower effective DC voltage

16b The smaller the ripple voltage the bigger the effective DC voltage

Care needs to be taken when making comparisons between power supplies with regard to ripple voltage. For example, two different power supplies may have a ripple voltage specification of 100mVp-p but if they have different maximum output voltage ($Vout_{(max)}$) then one is a better power supply than the other.

This is why the ripple as a percentage of the effective DC voltage is often given in manufacturers specifications for power supplies. This figure is calculated using the equation:

$$Ripple\ percentage = \frac{Vout_{(ripple)(RMS)}}{Vout_{(DC)}} \times 100$$

The smaller the value for the ripple percentage, the better the power supply.

Notice in the equation above that the RMS value of the ripple is used. Calculating the exact RMS value of ripple voltage requires calculus (integration) which you're not expected to be able to do. However, calculating RMS using the equation $Vout_{(ripple)(RMS)} = 0.707 \times Vout_{(ripple)(pk)}$ is a close enough approximation for our purposes.

Practise finding the ripple voltage, effective DC voltage and ripple factor of a power supply by trying the following questions.

1. Determine from the graph in Figure 17 below the maximum output voltage ($Vout_{(max)}$) of a loaded power supply with the measured performance shown.

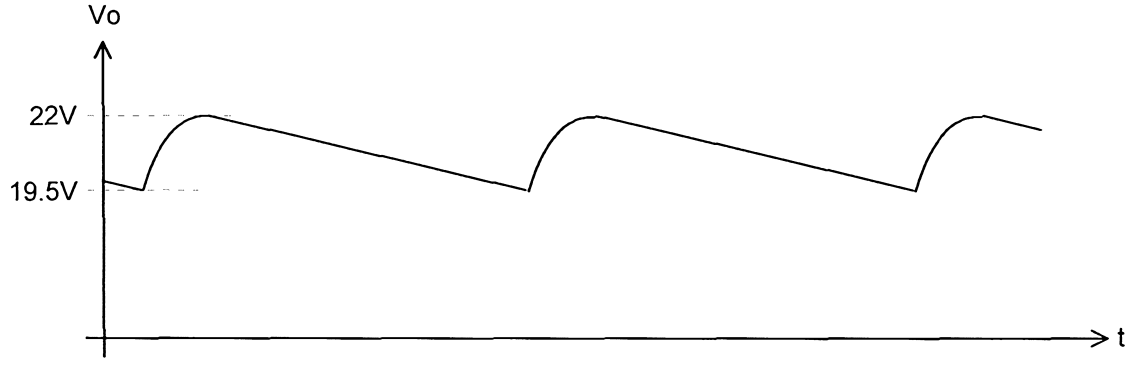


Figure 17

2. Calculate the power supply's ripple voltage ($Vout_{(ripple)}$).

3. Calculate the power supply's effective DC output voltage ($Vout_{(DC)}$).

4. Calculate the power supply output's ripple percentage.

5. Which voltage would a DC voltmeter measure if it was used to measure the output voltage?

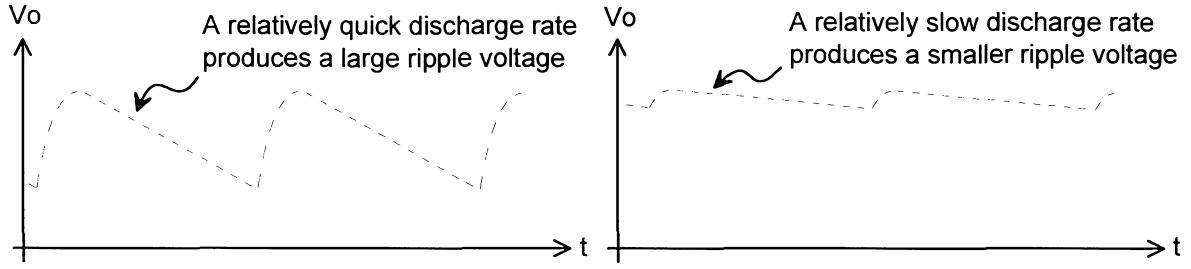
- ☐ 20.75V
- ☐ 19.5V
- ☐ 22V
- ☐ 2.5V

6. What would the meter measure if the load was disconnected?

- ☐ 20.75V
- ☐ 19.5V
- ☐ 22V
- ☐ 2.5V

Factors affecting ripple voltage

As you have seen, a ripple voltage is developed at the output of a loaded DC power supply because the filter capacitor discharges through the load while the rectifier diode is turned off. The size of the ripple voltage is determined by the rate at which the capacitor discharges into the load. If the rate of discharge is relatively high (that is, the capacitor discharges quickly), the ripple is large (see Figure 18a). If the rate of discharge is relatively low (that is, the capacitor discharges slowly) then the ripple is small (see Figure 18b).



18a **18b**

Obviously then, to minimise the size of the ripple voltage, the rate at which the filter capacitor discharges must be slowed down.

Recall that a capacitor in an RC circuit fully discharges in five time constants. Recall also that the time constant is determined by the values of resistance and capacitance and calculated using the equation $\tau = RC$. From the equation it is clear that if the value of either the resistance or the capacitance increases then the time constant and the time it takes to discharge also increases. In turn, this would reduce the size of the ripple.

That being the case, to minimise the ripple voltage out of a loaded DC power supply, either the load's resistance or the filter capacitor's size must be as large as practical. However, as the load of a power supply is usually a circuit of some sort, it will exhibit a resistance that realistically cannot be changed. So, in practice, designers of circuits choose a large value of filter capacitance. Filter capacitance values in the order of 10,000μF to 100,000μF (and beyond) are common. The exact value of filter capacitance needed for a given load and ripple percentage can be calculated but this is not necessary for technicians to be able to do.

As mentioned in the last section, one of the main advantages of the full-wave rectifier over the half-wave rectifier is that it is easier to smooth its pulsating DC output. Specifically, a full-wave rectifier has half the amount of ripple voltage of a half-wave rectifier with the same value of filter capacitance connected to the same load.

To explain why, consider the two graphs below. Figure 19 shows the ripple caused by the discharge rate of a capacitor in a half-wave rectifier. Figure 20 shows a full-wave rectifier with a filter capacitor having the same rate of discharge (so the load resistance and filter capacitance values are the same as for the half-wave rectifier). But, because the pulses of DC occur twice as often (that is, at 100Hz instead of 50Hz) the capacitor isn't allowed to discharge as much before being topped-up again. That being the case, the output ripple voltage is half the amplitude.

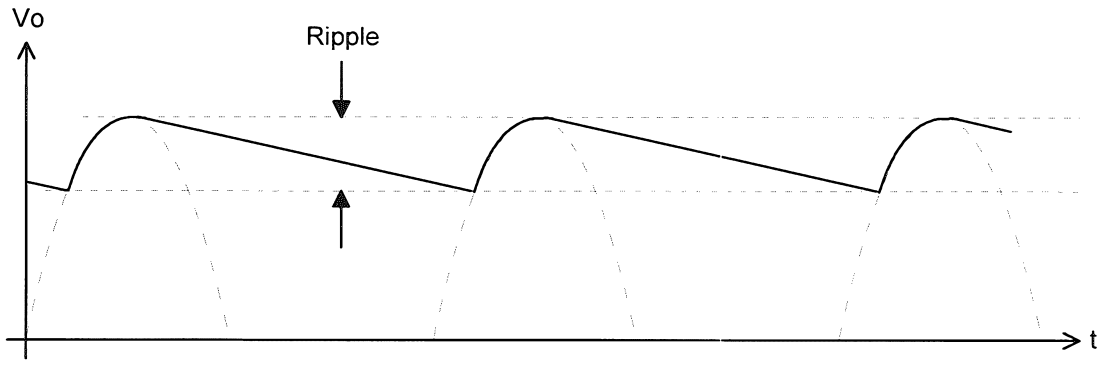


Figure 19 *The output of a filtered half-wave rectifier with a given value of load resistance and filter capacitance*

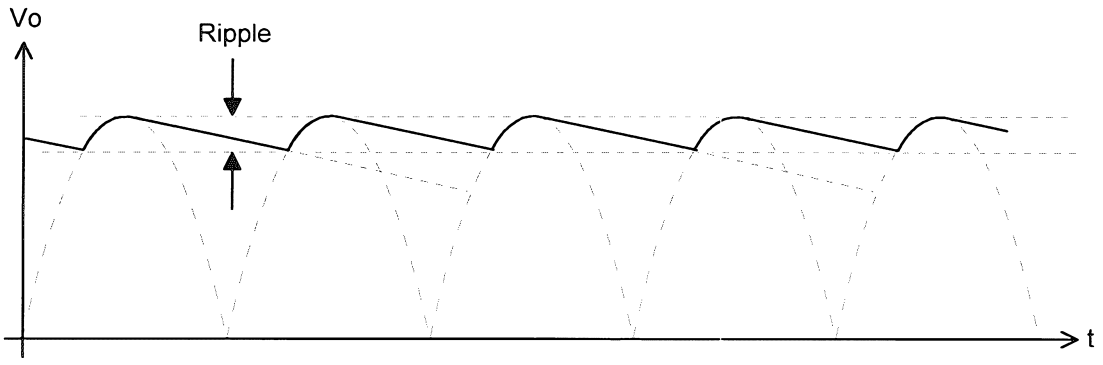


Figure 20 *The output of a filtered full-wave rectifier with the same values of load resistance and filter capacitance*

It's for this reason that full-wave rectifiers are preferred over the half-wave rectifier for the power supply of most electronics equipment.

Filter capacitor considerations

The filter capacitor affects the minimum value of reverse breakdown voltage that can be used for rectifier diodes in the half-wave rectifier circuit.

Recall that the peak inverse voltage (*PIV*) experienced by the diode in the half-wave rectifier without a filter capacitor is equal to the negative peak of the transformer's secondary voltage (that is, $PIV = -Vpk$). However, with a filter capacitor in the circuit the PIV experienced by the diode(s) is almost twice this.

To explain, consider the circuit of a filtered half-wave rectifier in Figure 21 below. As the secondary voltage passes the positive peak voltage the capacitor is topped-up to the maximum output voltage ($Vout_{(max)}$). And, if the power supply is well designed it shouldn't change much from that value. So, when the secondary voltage reaches the negative peak, the potential difference across the diode is from the negative peak voltage to the maximum output voltage.

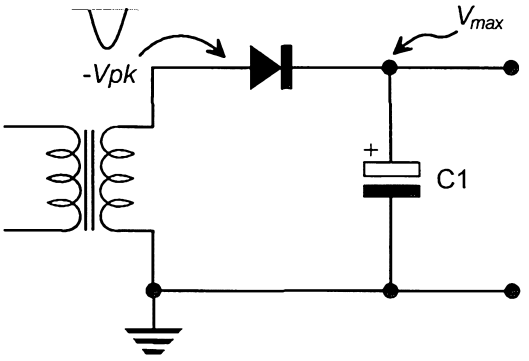


Figure 21 *The PIV experienced by the diode of the filtered half-wave rectifier is almost twice that experienced by the unfiltered half-wave rectifier*

For convenience we simply say that the peak inverse voltage experienced by the diode(s) in filtered the half-wave rectifier is:

$$PIV = 2 \times -Vpk$$

Another filter capacitor consideration is a very practical one. Although large value filter capacitors minimise ripple voltage they can be physically very large as well. This may be a problem if the equipment is required to be physically small.

A simple solution to this problem is to use several smaller value (and hence physically smaller) capacitors connected in parallel. So, 100,000μF of capacitance can be achieved by one large 100,000μF capacitor or by three smaller 33,000μF connected in parallel.

[Note: Obtaining large values of filter capacitance using parallel combinations of smaller value capacitors has other advantages but we'll leave these to another subject.]

How does the filter capacitor get its name?

There's another way to think about the smoothing action of the capacitor that involves filter theory. It also explains how the capacitor gets its name.

The voltage out of a rectifier is a complex waveform that contains both AC and DC components. Recall that capacitors act like an open-circuit to DC but act like a low resistance or even a short-circuit to AC. That being the case, with the filter capacitor connected across the output of a rectifier, the ripple voltage (which is an AC component) is short-circuited around the load while the DC component is allowed to reach the load. This is shown in Figure 22 below.

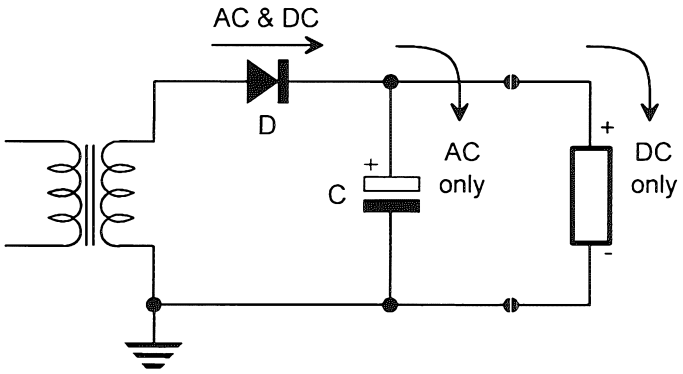


Figure 22 *The filter capacitor forces the AC current to by-pass the load*

Faults with capacitor smoothing

Filter capacitors are usually electrolytic (the aluminium electrolyte type). These types of capacitor generally experience one of two problems. First, they can go open-circuit. What would be the effect of this at the power supply's output? Second, they can go "leaky". That is, they behave as though they have a large value resistor connected across them. What would be the effect of this at the power supply's output?

When replacing faulty filter caps, there are two main considerations. First, you must choose a replacement with the same capacitance or better than the original. Second, you must choose a replacement with the same working voltage or better than the original.

Other smoothing circuits

There are two other methods used for smoothing the pulsating DC output of a rectifier. One uses both an inductor and a capacitor (see Figure 23) and the other uses an inductor and two capacitors (see Figure 24).

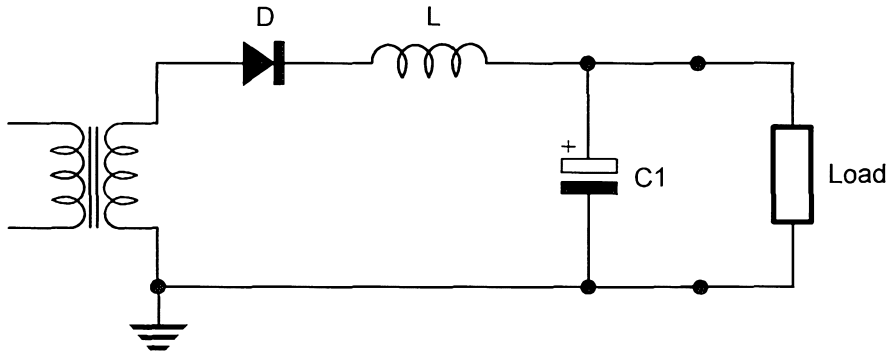


Figure 23 *Smoothing the output of a half-wave rectifier using an inductor instead of a capacitor*

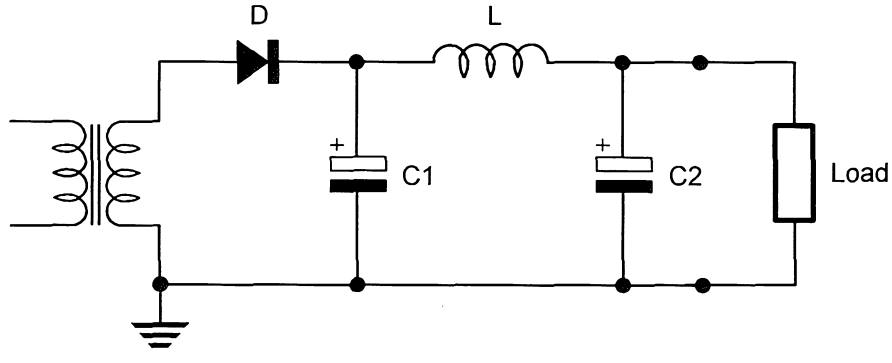


Figure 24 *Smoothing the output of a half-wave rectifier using an inductor and two capacitors*

These methods of smoothing are much less common and are only used in specialised applications. As such, their operation will not be discussed here and you will not be asked any questions on them in the theory tests.

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Student notes

Skill practice 4

Practise measuring the key potential differences (including ripple) in filtered half-wave rectifier and filtered full-wave rectifier circuits using a DMM and an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1½ hours to complete this exercise.

Equipment

- 15V AC power supply
- prototyping panel
- DMM
- four 1N4004 diodes
- 100µF 35V capacitor
- 220µF 35V capacitor
- 470µF 35V capacitor
- 1000µF 35V capacitor
- 330Ω 5W resistor
- two BNC to alligator-clip leads
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the breadboard. Make sure that you connect the filter capacitor in the correct polarity.

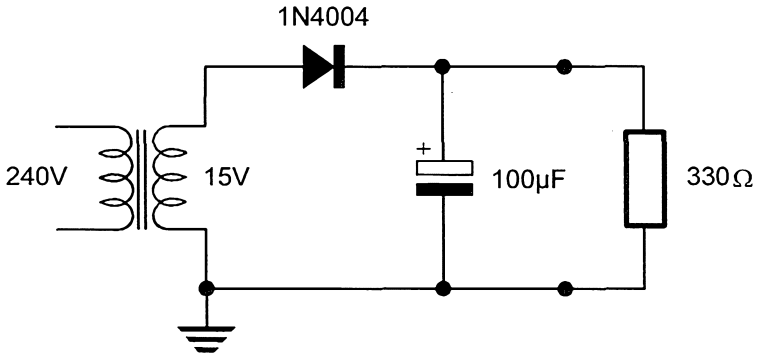


Figure 1

4. Connect the CRO's channel 1 input across the secondary winding.

5. Connect the CRO's channel 2 input across the load resistor.

6. Adjust the CRO so that it displays both channels.

7. Set the CRO's input coupling control of both channels to the *GND* position.

8. Adjust channel 1's trace so that it is aligned with one of the display's horizontal lines below the middle line.

9. Adjust channel 2's trace so that it is on top of channel 1's trace.

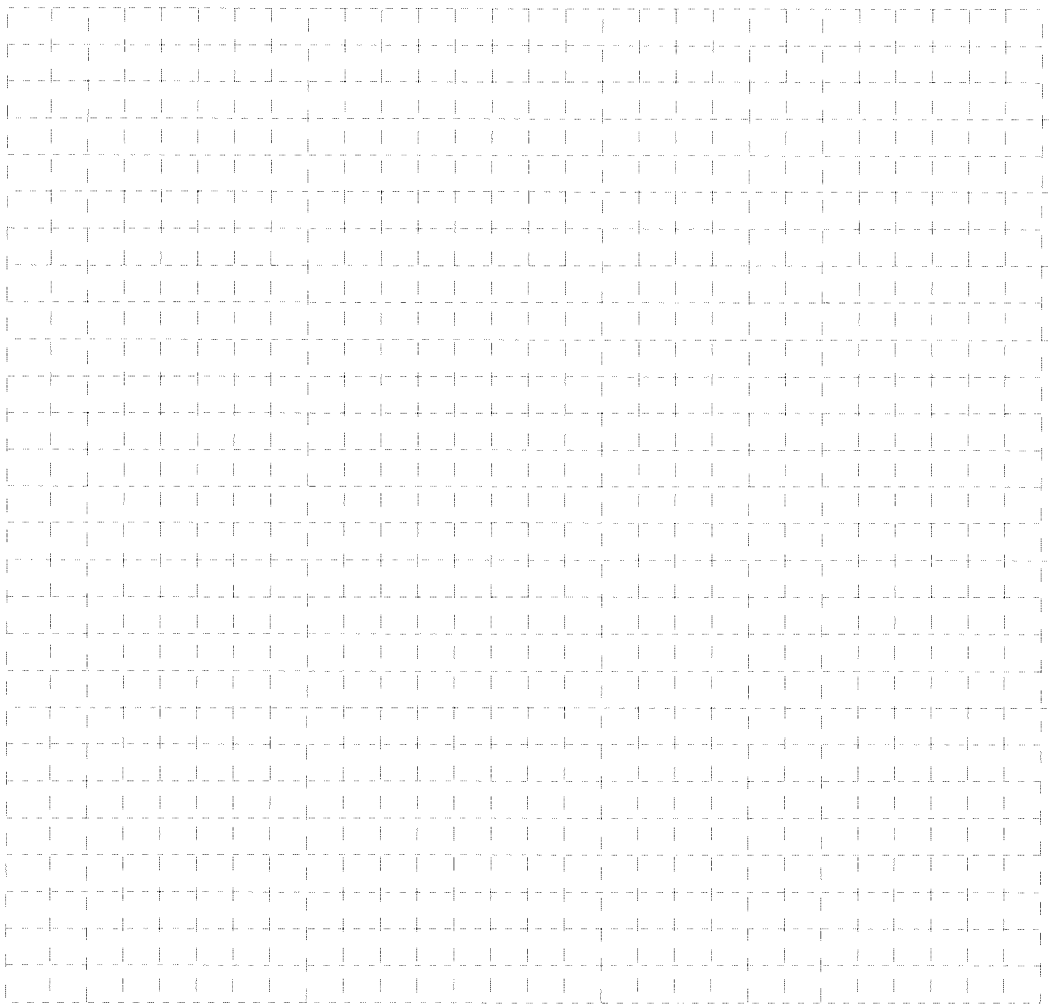
10. Set the input coupling control of both channels to the *DC* position.

11. Set the vertical attenuation (volts/div) control of both channels to 10V/div.

12. Turn on the power supply.

13. Adjust the CRO so that you view two or so cycles of the secondary.

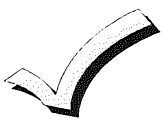
14. Draw both signals time coincident with each other on the graph on the next page clearly showing the 0V reference. (**Note:** Try to use the whole of the graph paper.)



15. Accurately measure the secondary's peak voltage and show this value on your graph.

16. Set the vertical attenuation (volts/div) control of channel 2 to 5V/div.

17. Accurately measure the load's maximum output voltage $Vout_{(max)}$ and show this value on your graph also.



The teacher needs to check your work at this point...

18. Measure the load's maximum output voltage ($Vout_{(max)}$) and record this in Table 1 below.

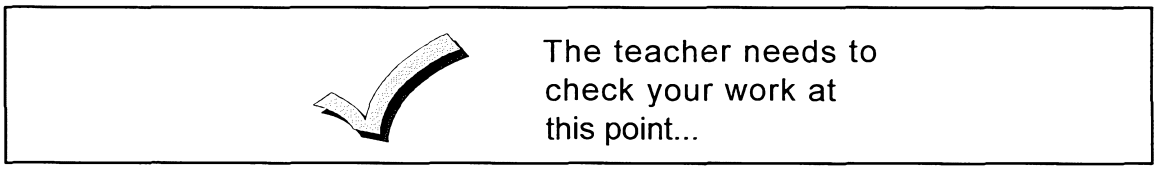
19. Measure and record the peak-to-peak output ripple voltage ($Vout_{(ripple)}$) using the CRO.

    Note: To do this accurately you'll have to switch the input coupling control for channel 2 to the AC position then adjust the *Vertical Attenuation* control to make the signal bigger on the screen.

20. Measure the load voltage with the **DMM**. Record this in the $Vout_{(DC)}$ column.

21. Calculate and record the ripple percentage using the equation: $ripple\ \% = \frac{Vout_{(ripple)(RMS)}}{Vout_{(DC)}} \times 100$.

22. Measure and record the frequency of the ripple voltage.

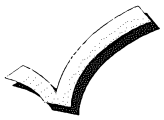


23. Replace the 100µF capacitor with the next value in Table 1 and repeat Steps 18 to 22.

24. Repeat Steps 18 to 22 for the remaining filter capacitors listed in Table 1.

Table 1

Capacitor	$Vout_{(max)}$	$Vout_{(ripple)}$	$Vout_{(DC)}$	ripple %	Ripple frequency
100µF					
220µF					
470µF					
1,000µF					



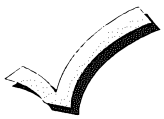
The teacher needs to check your work at this point...

Question 1
From the results in Table 1, what is the relationship between the filter capacitor's value and the ripple voltage?

Question 2
What is the relationship between the filter capacitor's value and the ripple percentage?

Question 3
Does the filter capacitor's value affect the ripple frequency?

Question 4
From your experience in this practical so far, what is a useful purpose for the *Input Coupling* control on the CRO?



The teacher needs to check your work at this point...

25. Completely dismantle the current circuit and wire the circuit of Figure 2 below.

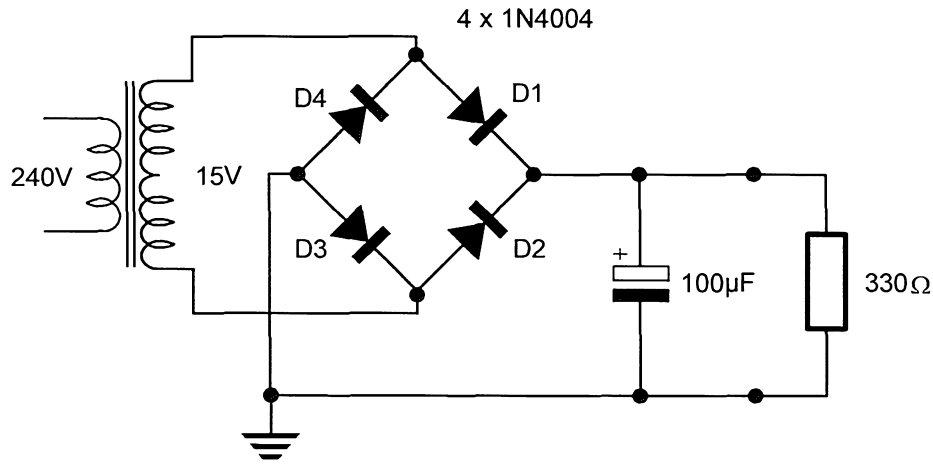


Figure 2

26. Measure the maximum output voltage ($Vout_{(max)}$) using the CRO's channel 1 input. Record this in Table 2 below. [Note: Don't measure the secondary voltage as it trips the breaker on the AC power supply.]

27. Measure and record the peak-to-peak value of the output ripple voltage ($Vout_{(ripple)}$) using the CRO.

28. Measure and record the load voltage with the DMM.

29. Calculate and record the ripple percentage.

30. Measure and record the frequency of the ripple voltage.

Table 2

Capacitor	$Vout_{(max)}$	$Vout_{(ripple)}$	$Vout_{(DC)}$	ripple %	Ripple frequency
100µF					

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Question 5
Why is the ripple frequency double the ripple frequency of the circuit in Figure 1?

Question 6
Why is the ripple voltage smaller for the bridge rectifier with a 100μF filter capacitor than it was for the half-wave rectifier with the same value capacitor (see your results in the first row of Table 1)?

Question 7
Summarise the benefits of using a filtered full-wave rectifier over a filtered half-wave rectifier in terms of the quality of the DC voltage produced.

The teacher needs to check your work at this point...

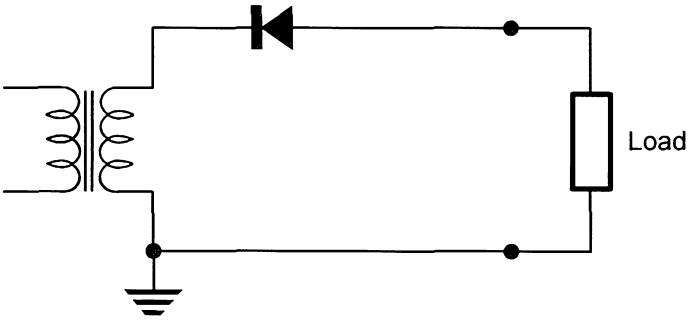
Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

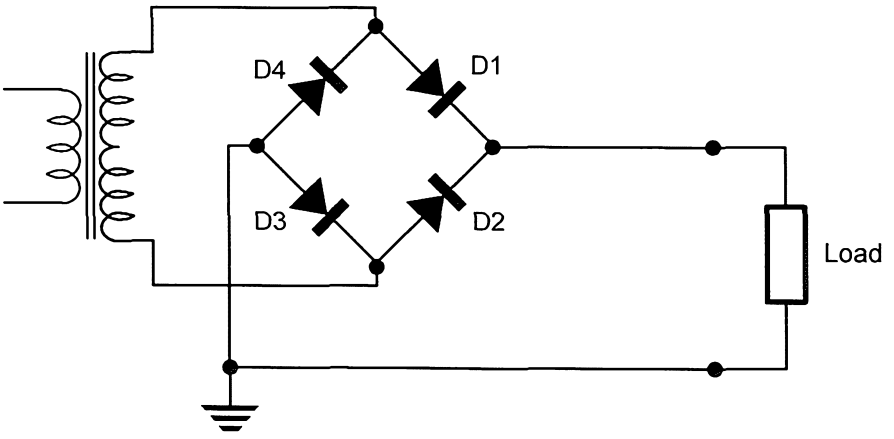
1. What is the filter capacitor's purpose in a DC power supply?

2. Show on the following rectifier circuits how a filter capacitor would be connected to the circuit in the correct polarity. [Note: Be careful, some of the circuits produce a negative output voltage.]

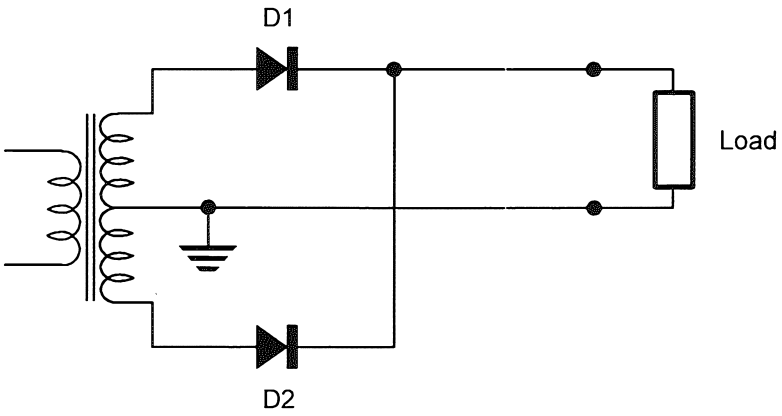
(a)



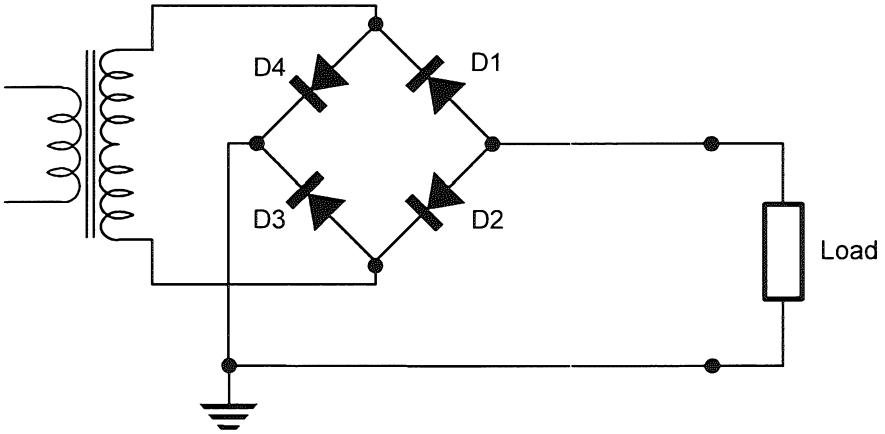
(b)



(c)



(d)



3. Why is the filter capacitor usually an electrolytic type?

4. When does the filter capacitor discharge into the load?

Questions 5 to 13 refer to a filtered half-wave rectifier with the measured performance shown in Figure 1

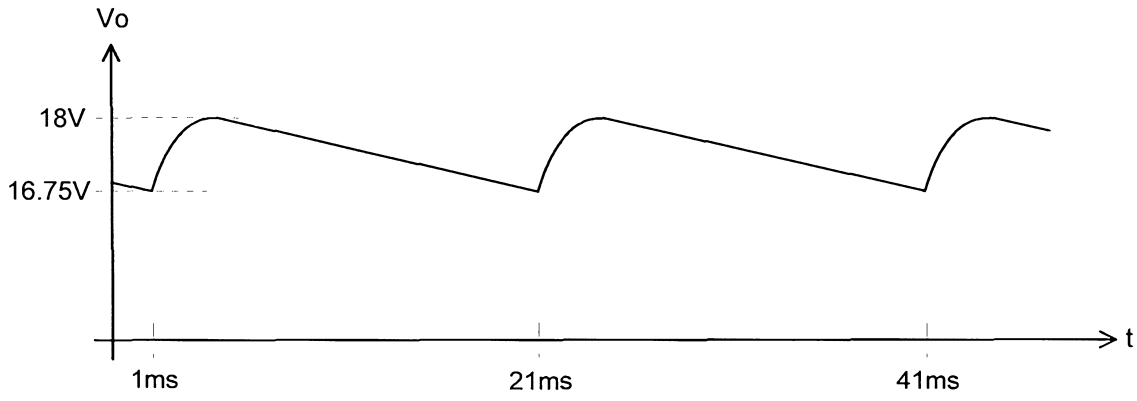


Figure 1

5. What is the period of the ripple?

_____

6. What is the ripple frequency?

_____

_____

7. Determine from the graph the maximum output voltage ($Vout_{(max)}$).

_____

8. Calculate the peak-to-peak value of the output ripple voltage ($Vout_{(ripple)}$).

_____

_____

9. Calculate the effective DC output voltage ($Vout_{(DC)}$).

_____

_____

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10. Calculate the ripple percentage.

11. Is a power supply with a ripple percentage of 1.3% better than this one? Explain your answer.

12. Which voltage would a meter measure if it was used to measure the output voltage?

- ☐ 1.25V
- ☐ 16.75V
- ☐ 17.375V
- ☐ 18V

13. What would a meter measure if the load was disconnected?

- ☐ 1.25V
- ☐ 16.75V
- ☐ 17.375V
- ☐ 18V

14. What **three** factors affect the size of the ripple voltage out of a filtered rectifier?

15. In practice, what two things can be done to minimise the ripple voltage out of power supplies?

16. For a given value of filter capacitance and load resistance, the ripple voltage out of a full-wave rectifier is

- ☐ half the ripple voltage out of a half-wave rectifier.
- ☐ twice the ripple voltage out of a half-wave rectifier.
- ☐ the same as the ripple voltage out of a half-wave rectifier.

17. What is the ideal amount of ripple voltage out of a DC power supply?

18. What voltage would the effective DC output voltage be the same as if the output ripple voltage is 0V?

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Questions 19 to 24 refer to a filtered full-wave rectifier with the measured performance shown in Figure 2

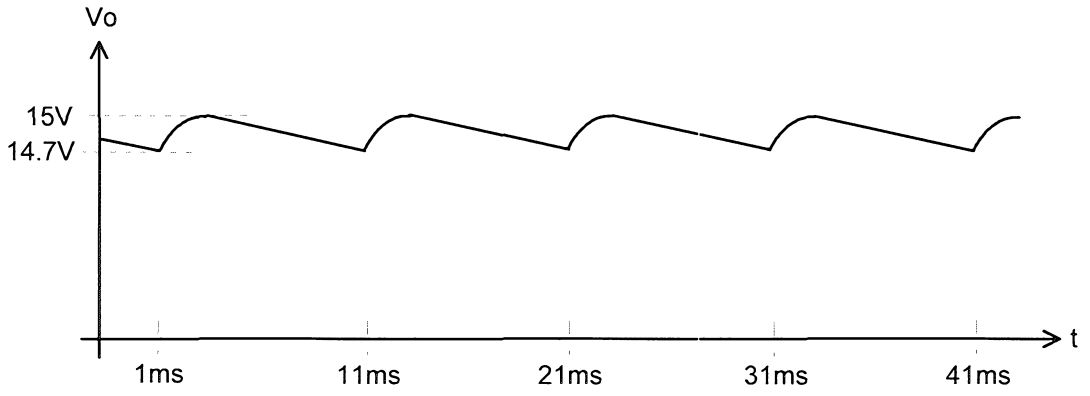

Figure 2

19. What is the period of the ripple?

20. What is the ripple frequency?

21. Determine from the graph the maximum output voltage ($Vout_{(max)}$).

22. Calculate the peak-to-peak output ripple voltage ($Vout_{(ripple)}$).

23. Calculate the effective DC output voltage $(Vout_{(DC)})$.

24. Calculate the ripple percentage.

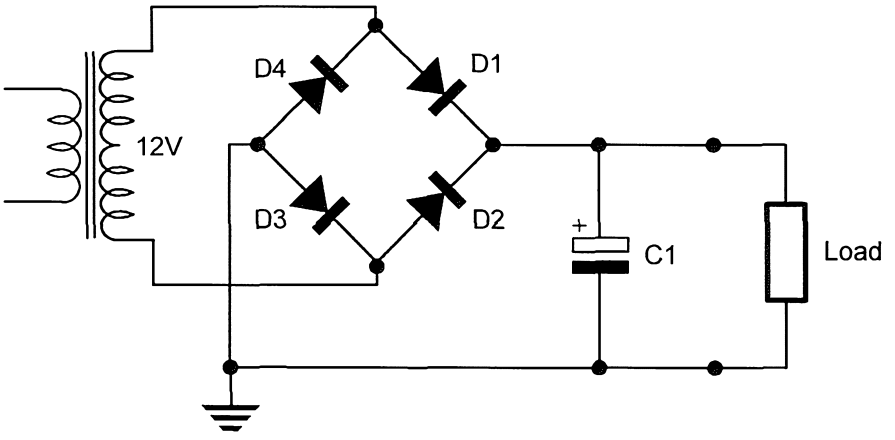

Figure 3

25. What is the peak inverse voltage experienced by the diodes in the rectifier in Figure 3?

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Student notes

Section 5 Dual rail power supplies and fault-finding

Purpose To develop your ability to use test equipment to test unregulated single rail and dual rail power supply circuits, recognise when the circuit is faulty, and identify the likely faulty component.

Objectives At the end of this section you should be able to:

- Draw and explain the operation of various filtered rectifier circuits that simultaneously provide a positive and negative DC output voltage
- List the faults that can occur with filtered rectifier circuits
- Describe the effect of each of these faults on the performance of filtered rectifier circuits
- Measure key potential differences around faulty unregulated powers supplies using a DMM and oscilloscope to identify the likely faulty component and what is wrong with it

Introduction

While many electronics circuits require only a single rail power supply for operation (either positive or negative), there are many components and circuits that have better performance characteristics when operating from both a positive and a negative rail. That being the case, you will encounter dual rail power supplies in your time as a component-level repair technician and you'll almost certainly be required to repair some.

This section introduces you to several dual rail power supply circuits and common faults that single rail and dual rail power supplies can experience.

The dual rail half-wave rectifier

Recall that the half-wave rectifier can be used to produce either a positive or negative output voltage as shown in Figures 1a and 1b.

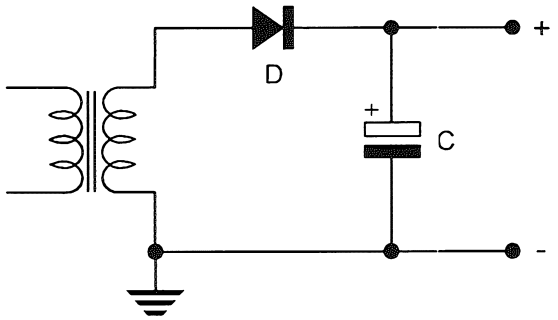

Figure 1a *Positive output voltage half-wave rectifier*

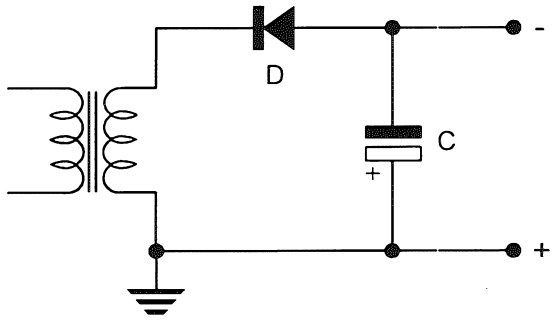

Figure 1b *Negative output voltage half-wave rectifier*

To wire a dual rail half-wave rectifier, all that is required is to combine these two circuits and use a centre-tapped transformer in place of having two individual transformers (see Figure 2).

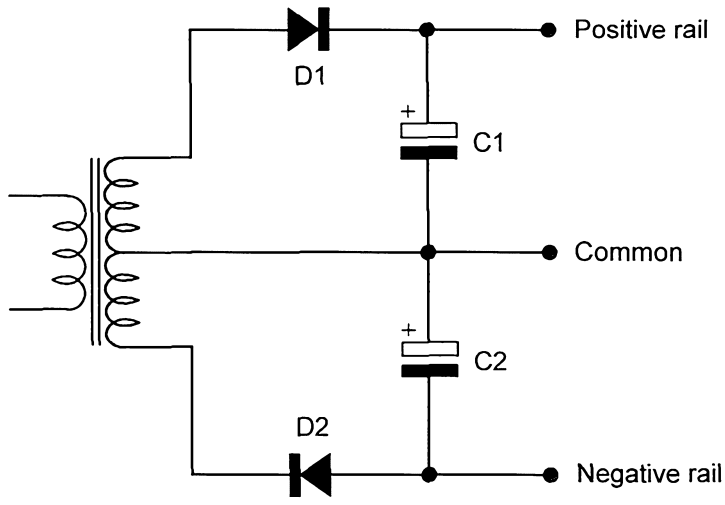

Figure 2 *A dual rail half-wave rectifier*

The circuit's common (or 0V reference) is connected to the centre-tap on the transformer and it is also usually connected to ground (though this is by good practice rather than necessity). As there are two diodes, it is easy to confuse the dual rail half-wave rectifier with the single rail full-wave rectifier (see Figure 3 below). Compare the two circuits and notice the differences.

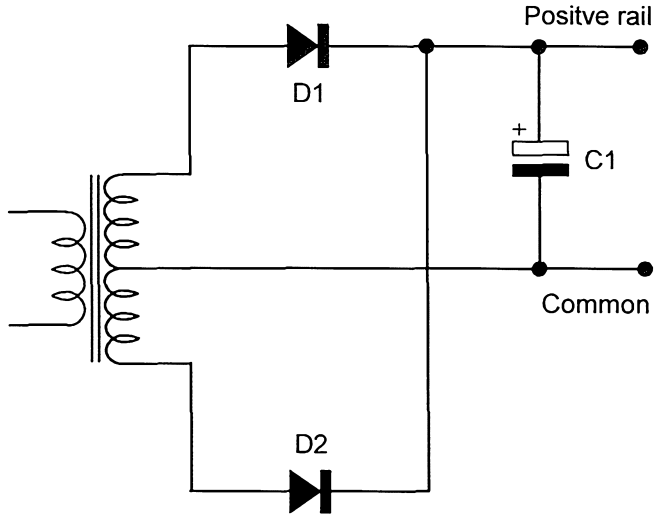

Figure 3 *There are obvious differences between these two circuits when you compare them side-by-side*

The dual rail full-wave rectifier

Recall that the full-wave rectifier can be used to produce either a positive or negative output voltage as shown in Figures 4a and 4b.

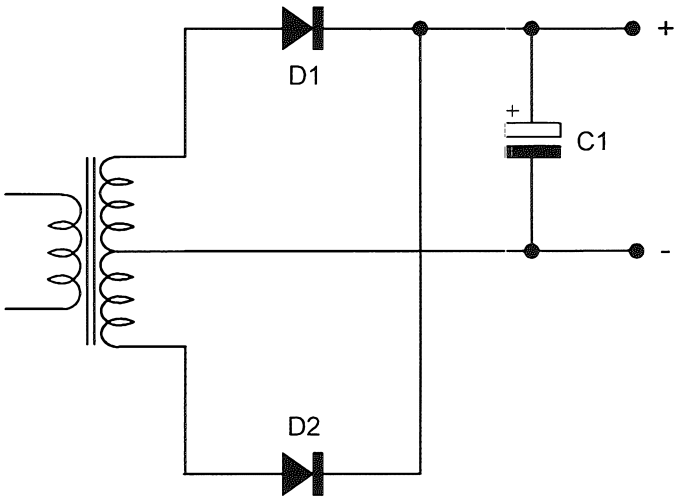

Figure 4a *Positive output voltage full-wave rectifier*

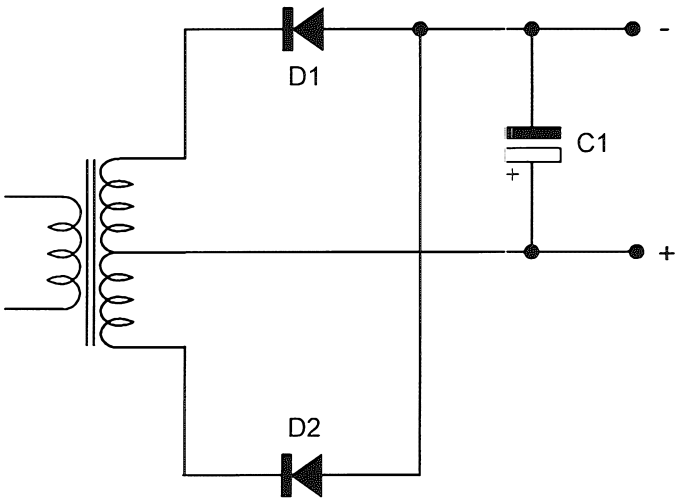

Figure 4b *Negative output voltage full-wave rectifier*

To wire a dual rail full-wave rectifier, all that is required is to combine these two circuits (see Figure 5).

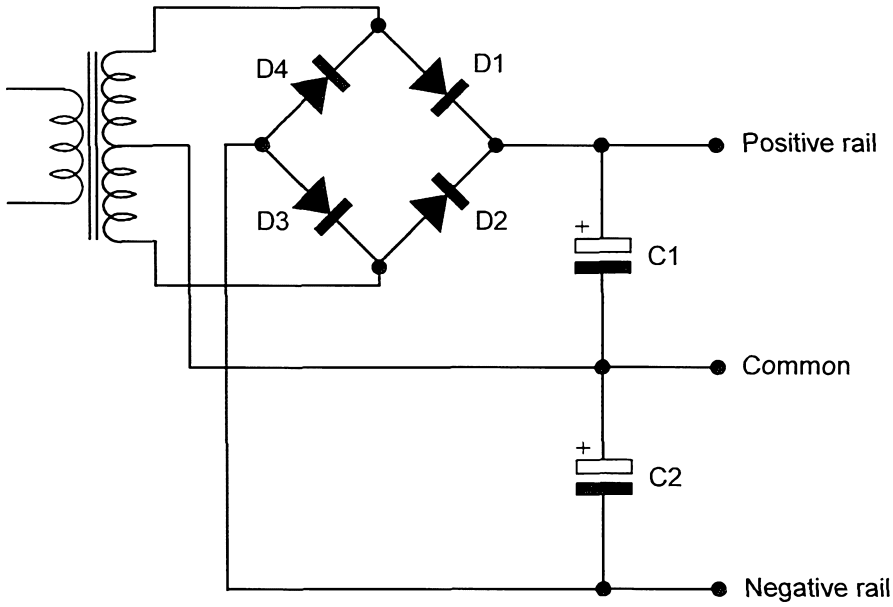

Figure 5 *A dual rail centre-tapped transformer full-wave rectifier*

As there are four diodes, it is easy to confuse the dual rail full-wave rectifier with the single rail bridge rectifier (see Figure 6 below). Compare the two circuits and notice the differences.

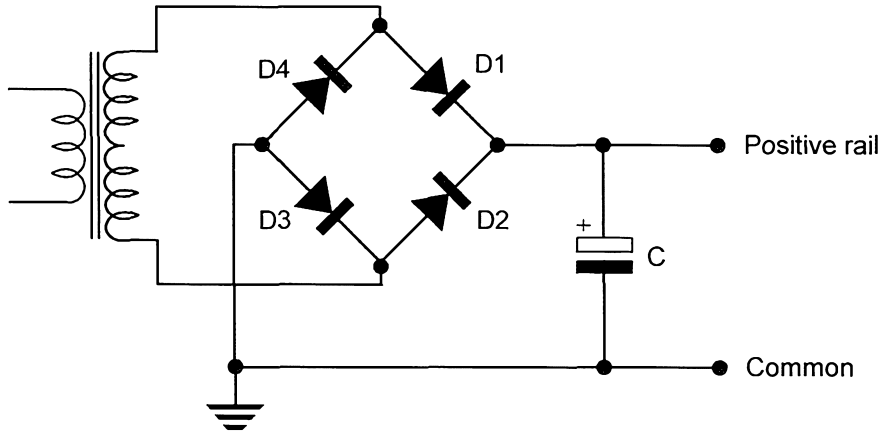

Figure 6 *There are obvious differences between these two circuits when you compare them side-by-side*

The operation of the dual rail full-wave rectifier may not be immediately obvious so an explanation follows. When the secondary voltages are in the polarity indicated in Figure 7 below, *D1* and *D3* are forward biased and current flows in the direction shown topping up the capacitors and passing through both loads.

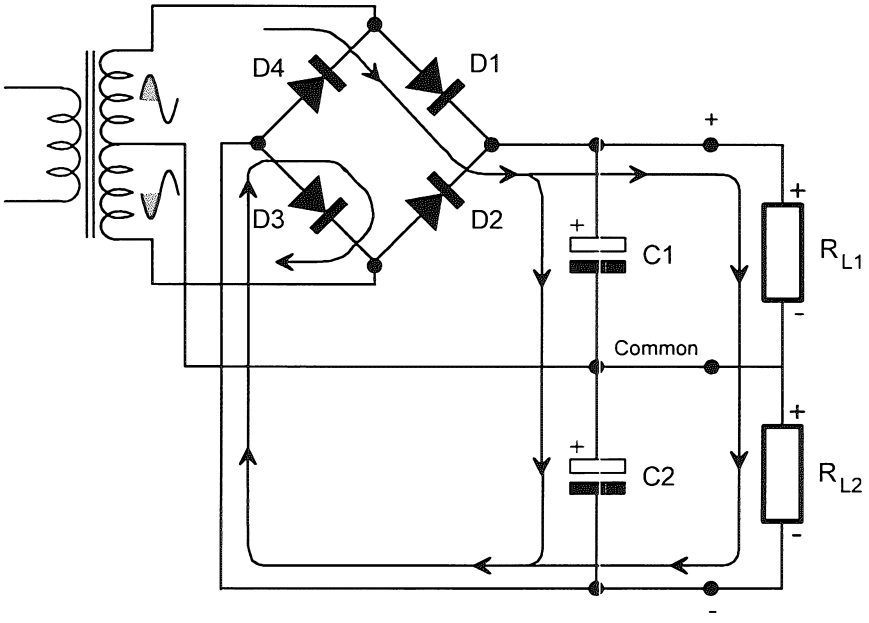

Figure 7 *The currents around the circuit of a dual rail full-wave rectifier during the secondary voltages highlighted*

The polarity of the potential difference developed across R_{L1} is such that the negative side of the load is connected to the common. So, the output voltage is positive with respect to common and this is the supply's positive output. However, the polarity of the potential difference developed across R_{L2} is such that the positive side of the load is connected to the common. So, the output voltage is negative with respect to common and this is the supply's negative output.

When the polarity of the secondary voltages reverses, current passes through the loads in the same direction because diodes *D4* and *D2* are forward biased. This is shown in Figure 8 on the next page.

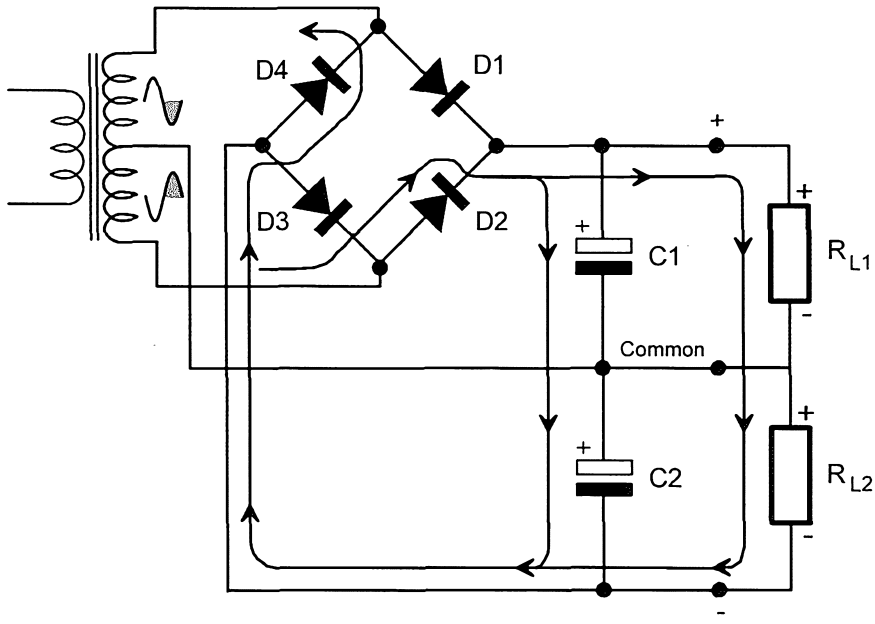

Figure 8 *The currents around the circuit of a dual rail full-wave rectifier during the secondary voltages highlighted*

The dual rail bridge rectifier

Recall that the bridge rectifier can be used to produce either a positive or negative output voltage as shown in Figures 9a (below) and 9b (on the next page).

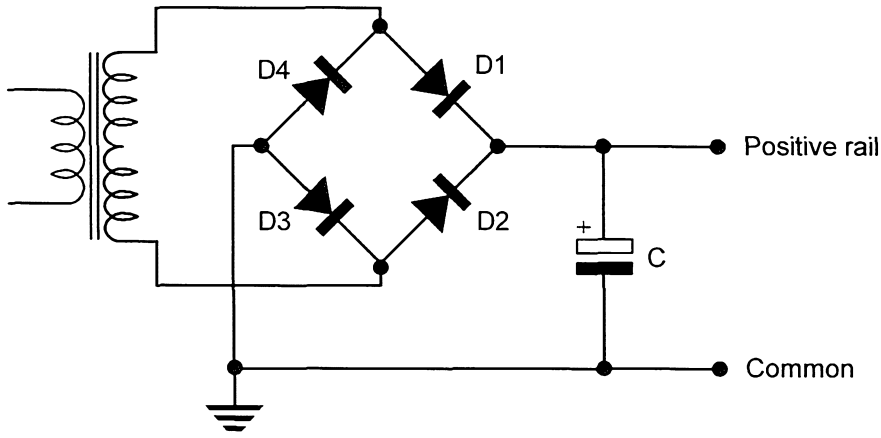

Figure 9a *Positive output voltage bridge rectifier*

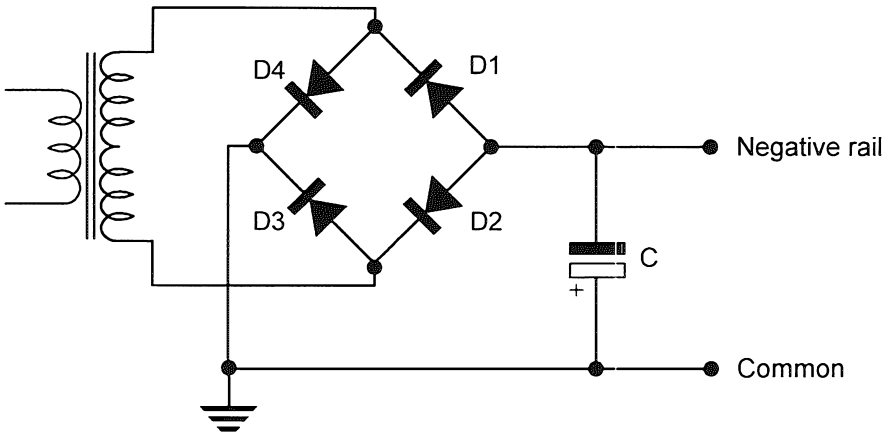

Figure 9b *Negative output voltage bridge rectifier*

To wire a dual rail full-wave rectifier, all that is required is to combine these two circuits (see Figure 10).

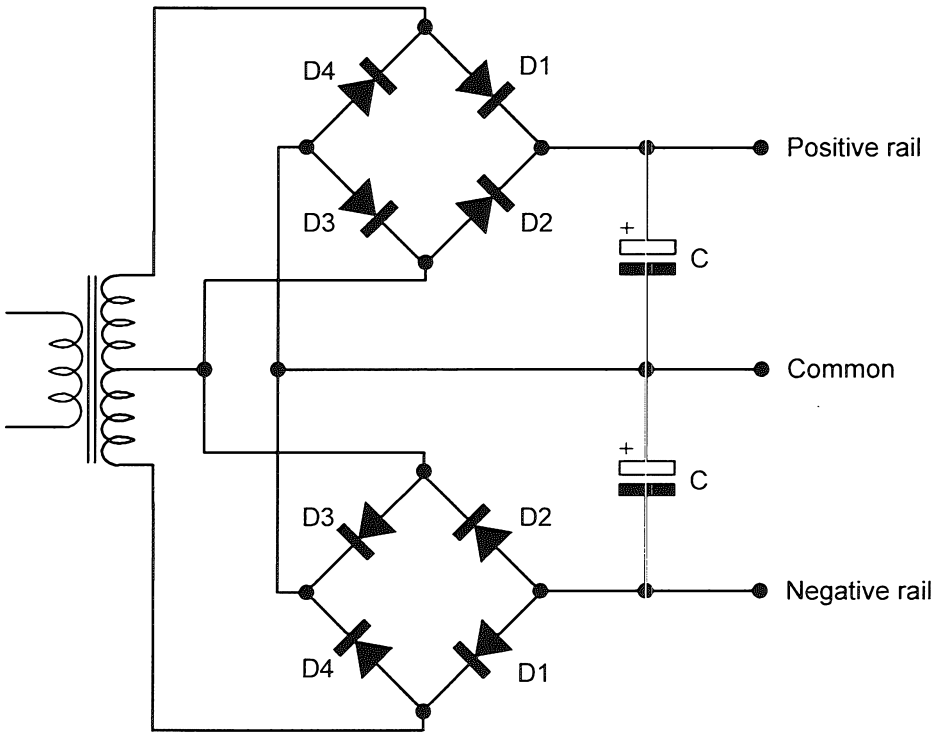

Figure 10 *A dual rail bridge rectifier*

Rectifier circuit faults

To be able to identify the component(s) causing the problem in a faulty rectifier circuit you need to know the job of each component in the circuit (and hopefully the subject so far has helped you in this regard). You also need to know about the kinds of faults that the components can experience. So, before we look at the effects of different faults, let's first consider the different ways that power supply components can go faulty.

Transformer faults

Transformer faults include:

- Short-circuit primary winding

  A manufacturing fault and/or a large primary current can cause the enamel that insulates the wire to breakdown. Without the insulation some or all of the turns of the primary winding can connect together or short. The effect of this fault would be to effectively reduce the number of windings in the primary which would increase the secondary voltage because the turns ratio (N) would go down.

- Open-circuit primary winding

  If the primary current is large enough it is even possible to melt the wire that the primary winding is made up of. Alternatively vibrations can cause metal fatigue in the wire causing it to break near an anchor point (like when you bend stiff metal wire backward and forward). This would open-circuit the primary winding which would cause the secondary voltage to drop to zero volts.

- Short-circuit secondary winding

  A short-circuit secondary winding can occur for the same reason as a short-circuit primary winding. The effect of this fault would be to reduce the secondary voltage because the turns ratio (N) would go up.

- Open-circuit secondary winding

  An open-circuit secondary winding can occur for the same reason as an open-circuit primary winding. The effect of this fault would be to reduce the secondary voltage to zero volts.

- Short-circuit between primary and secondary winding

  If the currents get large enough, the heat produced could melt the enamel around the wire of both the primary and secondary windings allowing them to touch each other and become a short-circuit. However, mains transformers play an extremely important part in isolating the equipment's circuitry from mains. That being the case, they are usually designed so that it is very unlikely that a short-circuit between the primary and the secondary can occur. In fact, the transformers in commercially sold electronics equipment must meet strict SAA rules in this regard.

  That said, it's perfectly legal to sell non-compliant transformers and so they can find their way into electronics equipment via hobbyists or repair technicians. So you can't assume that this type of fault is impossible so you must take appropriate care.

Rectifier diode faults
Rectifier diode faults include:

- Short-circuit anode-cathode

  Large voltage spikes in the mains are automatically transferred to the secondary via the transformer. These spikes can cause the rectifier diode to become short-circuit between the two terminals. Rectifiers diodes can also go short-circuit when another fault causes them to conduct too much current. When a diode becomes short-circuit it conducts in both directions all of the time.

- Open-circuit anode-cathode

  Large voltage spikes and excessive currents can cause diodes to go open-circuit instead. When a diode becomes open-circuit it will not conduct current in any direction.

Filter capacitor faults
Filter capacitors are usually large value (aluminium oxide) electrolytic capacitors and their faults include:

- Open-circuit

  Age and heat often cause the electrolyte inside aluminium oxide electrolytic capacitors to dry up. When this happens the capacitor can go open-circuit.

- Leaky

  Age and heat can cause capacitors to go leaky instead. When this happens the capacitor behaves as though it has a lower value of capacitance with a large value of resistance connected in parallel with it.

The following are the types of faults that a rectifier circuit can experience. They assume that, before the circuit became faulty, it was sufficiently filtered to produce a constant DC voltage with negligible ripple. It is also assumed that the rectifier circuit is loaded in the way that it would be in normal operation.

Higher than normal DC output voltage (no ripple)
Shown on a graph and compared to the normal output voltage, this fault would cause the output to look like Figure 11 below.

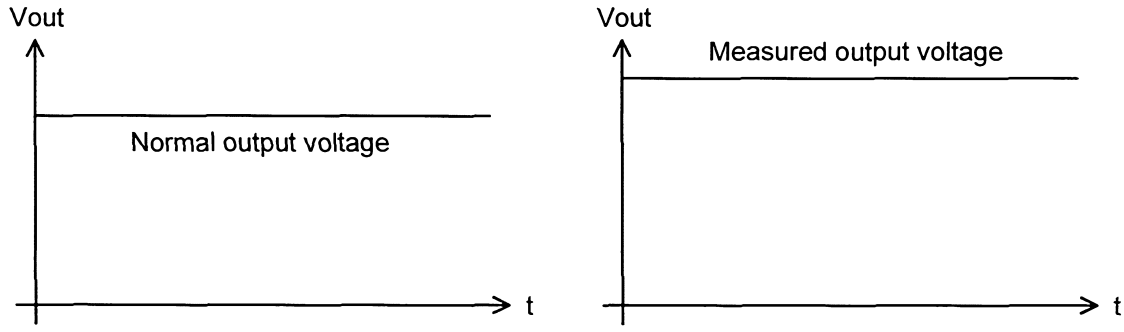

Figure 11

From this information we can deduce that the rectifier diode(s) and the filter capacitor are working normally because there is no ripple. That being the case, the larger output voltage can only be caused by a larger secondary voltage. One possible cause of a larger secondary voltage is an increase in the primary voltage (but this may be out of our control). Another possible cause is a short between some of the transformer's primary windings.

Lower than normal DC output voltage (no ripple)
Shown on a graph and compared to the normal output voltage, this fault would cause the output to look like Figure 12 below.

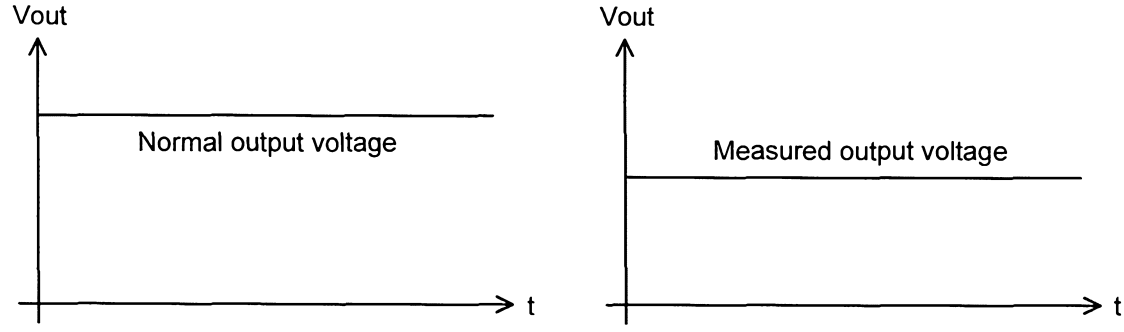

Figure 12

Again, from this information we can deduce that the rectifier diode(s) and the filter capacitor are working normally because there is no ripple. That being the case, the smaller output voltage can only be caused by a smaller secondary voltage. One possible cause of this is a decrease in the primary voltage (but this may be out of our control). Another possible cause is a short in the transformer's secondary windings.

Lower than normal DC output voltage and ripple
Shown on a graph, this fault would look like Figure 13 below.

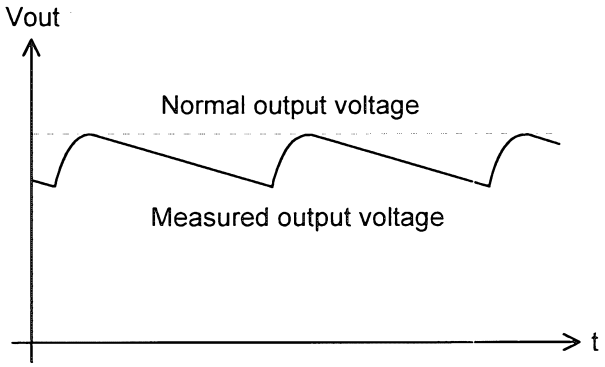

Figure 13

As there is more ripple in the output than there should be, it is clear that the capacitor is discharging too quickly and can't keep the output voltage constant.

The filter capacitor would discharge too quickly if the load has become an unusually small resistance (probably due to a fault somewhere else), if the capacitor has become leaky or if the rectifier circuit is a full-wave rectifier and one of the diodes has become an open-circuit.

It is possible to work out which of these faults is the more likely before you start taking out components. For example, if the period of the ripple is 10ms (which is a frequency of 100Hz) and the circuit is a full-wave rectifier then the ripple is the right frequency so the problem is not with one of the diodes.

The output voltage is entirely ripple
Shown on a graph, this fault would look like Figure 14a if the power supply uses a half-wave rectifier and Figure 14b if the power supply uses a full-wave rectifier.

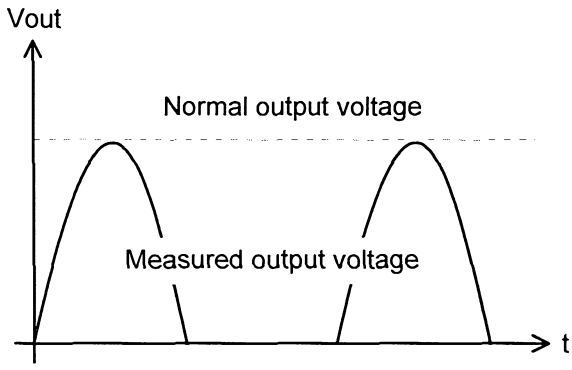

Figure 14a

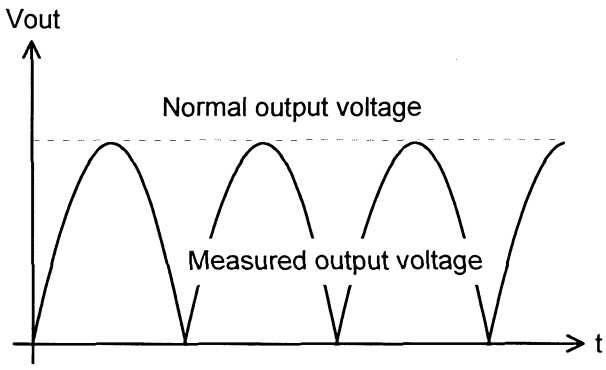

Figure 14b

From this information we can deduce that the problem lies with the filter capacitor and it has gone open-circuit.

No output voltage
Shown on a graph, this fault would look like Figure 15 below.

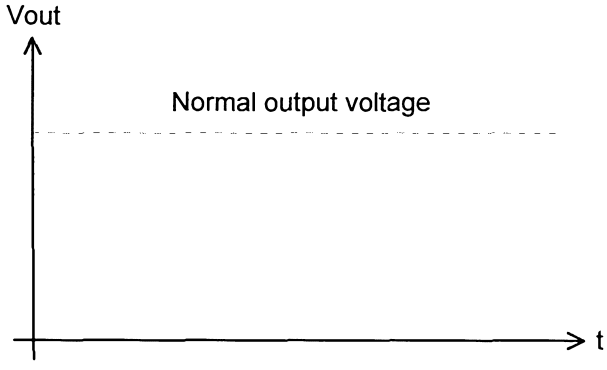

Figure 15

There are several possible causes of this. The most likely cause is a blown fuse (that is, it has gone open-circuit). However, simply replacing the fuse may not repair the power supply because fuses usually blow due another fault in the circuit. It is wise to visually inspect the circuit board and look for any obvious evidence of another fault (for example, cooked components). The next most likely cause is one or more of the rectifier diodes has gone open-circuit. Finally, the cause of the fault may be the transformer. It is possible that either the primary winding or the secondary winding has gone open-circuit.

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Student notes

Skill practice 5

Practise measuring key potential differences around faulty unregulated power supplies using a DMM and oscilloscope to identify the likely faulty component and what is wrong with it

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1 hour to complete this exercise.

Equipment

- Unregulated power supply panel
- DMM
- BNC to alligator-clip lead
- pin-to-pin leads

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 using the unregulated power supply panel.

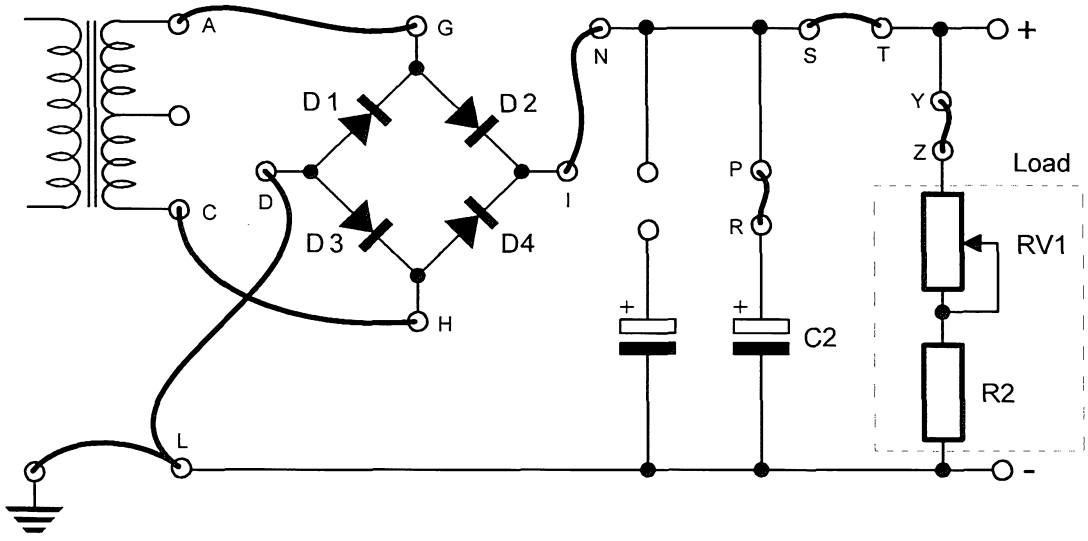


Figure 1

4. Set all the fault switches to the off position and turn on the power.

5. Adjust *RV1* so that it has minimum resistance (turn it fully clockwise).

6. Measure the voltage across the load using the DMM. Record your measurement in Table 1.

7. Measure and record the peak-to-peak ripple voltage across the load using the CRO.

8. Measure and record the RMS secondary voltage (between terminals "A" and "C") using the DMM. Don't forget to set the DMM for measuring AC.

Table 1

Load voltage	Ripple voltage	Secondary voltage

9. Turn on fault number 2.

10. Repeat steps 6 to 8 recording your results in Table 2 (below).

Table 2

Load voltage	Ripple voltage	Secondary voltage

11. Compare your measurements in Table 2 with the normal measurements in Table 1.

Question 1
What component fault is simulated by switch 2? Specifiy the component number and what you think is wrong with it.

The teacher needs to check your work at this point...

12. Turn off fault number 2.

13. Turn on fault number 3

14. Repeat steps 6 to 8 recording your results in Table 3 (below).

Table 3

Load voltage	Ripple voltage	Secondary voltage

15. Compare your measurements in Table 3 with the normal measurements in Table 1.

Question 2
What component fault is simulated by switch 3? Specifiy the component number and what you think is wrong with it.

_____

_____

_____

16. Turn off fault number 3.

17. Turn on fault number 4

18. Repeat steps 6 to 8 recording your results in Table 4 (below).

Table 4

Load voltage	Ripple voltage	Secondary voltage

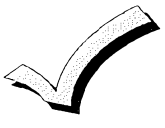
19. Compare your measurements in Table 4 with the normal measurements in Table 1.

Question 3
What component fault is simulated by switch 4? Specifiy the component number and what you think is wrong with it.

_____

_____

_____



The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 6 refer to the circuit in Figure 1

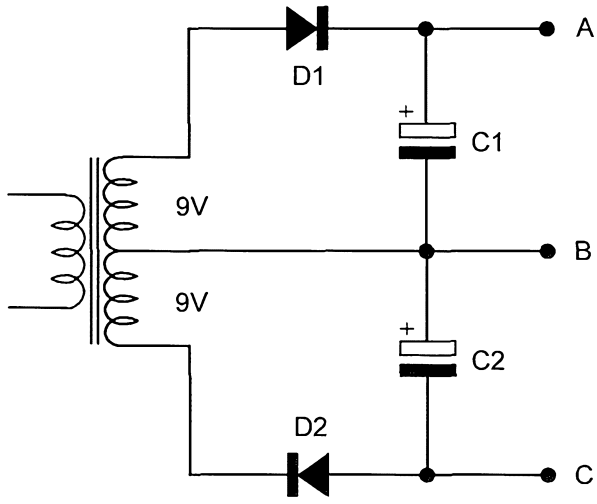

Figure 1

1. What is the circuit's full name?

   ☐ Single rail half-wave rectifier
   ☐ Single rail full-wave rectifier
   ☐ Dual rail half-wave rectifier
   ☐ Dual rail full-wave rectifier

2. Which point in the circuit is the common?

   ☐ A
   ☐ B
   ☐ C
   ☐ None of the above

3. Which two terminals must be used to connect the load to the negative supply?

- ☐ A and B
- ☐ A and C
- ☐ B and A
- ☐ B and C

4. What are the DC output voltages for the secondary voltages shown?

- ☐ +8.4V and -8.4V
- ☐ +9.6V and -9.6V
- ☐ +12.1V and -12.1V
- ☐ +24.8V and -24.8V

5. What two faults could cause the negative output to drop to 0V but not affect the positive output?

_____

_____

_____

6. What fault could cause the positive output to drop to +9V and contain ripple but not affect the negative output?

_____

_____

Questions 7 to 12 refer to the circuit in Figure 2

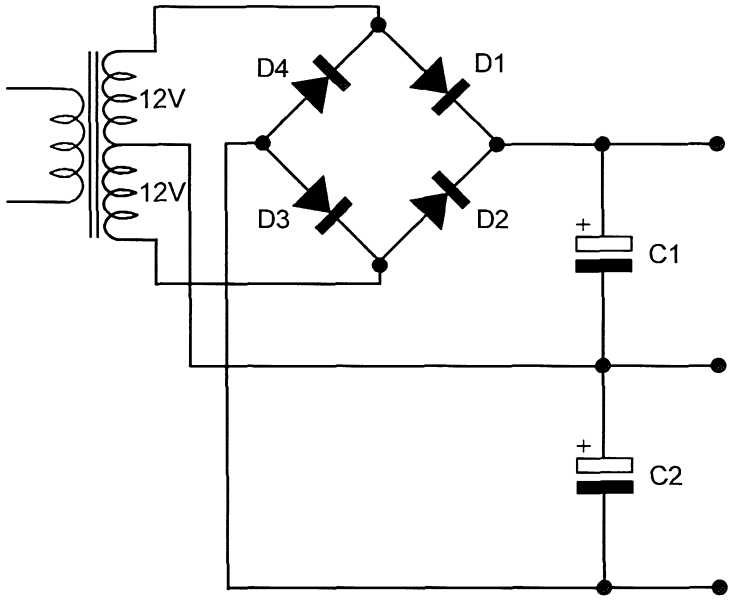

Figure 2

7. What is the circuit's full name?

- ☐ Single rail bridge rectifier
- ☐ Dual rail half-wave rectifier
- ☐ Dual rail full-wave rectifier
- ☐ Dual rail bridge rectifier

8. What are the DC output voltages for the secondary voltages shown?

- ☐ +16.4V and -16.4V
- ☐ +17.6V and -17.6V
- ☐ +15.8V and -15.8V
- ☐ +18.2V and -18.2V

9. What two faults could cause both outputs to drop to 0V?

10. What fault could cause the negative output to drop to -11V and contain a 100Hz ripple but not affect the positive output?

11. What fault could cause the positive output to drop to 12.5V and contain a 50Hz ripple but not affect the negative output?

12. What fault would cause the positive output to look like Figure 3 below but not affect the negative output?

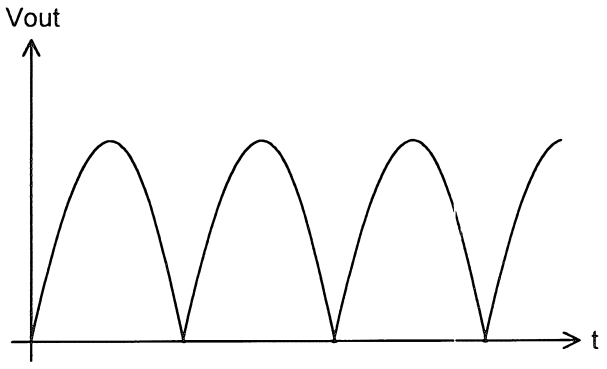

Figure 3

Section 6 Regulation

Purpose To develop your understanding of the need for additional circuitry used to keep the output voltage of a power supply as constant as possible.

Objectives At the end of this section you should be able to:

- Explain the need for a *regulator* in DC power supplies
- Explain the purpose of a regulator in DC power supplies
- Define the terms *load regulation* and *line regulation*
- Name the two regulator connections
- Explain the principle of operation of shunt and series regulation
- Calculate the (load) regulation percentage, the no-load output voltage or the full-load output voltage of a regulated power supply given two of the three quantities
- Measure the output voltage and current of a loaded unregulated power supply using a DMM

Introduction

So far, you have learnt that (linear) power supplies consist of a transformer to step-down the mains voltage and provide electrical isolation, a rectifier to convert the transformer's AC output to a pulsating DC and a smoothing circuit of some sort (usually a filter capacitor) to make the output voltage more constant or flat. A power supply consisting of only these three functional blocks is said to be *unregulated* and its output varies. Worse, this variation can upset the operation of the equipment that the power supply is operating.

For this reason, nearly all power supplies also include circuitry to implement a fourth functional block called *regulation*. This section explains why the output of unregulated power supplies varies and introduces you to the basic principles of regulation. Sections 7 and 8 explain the operation of some specific regulator circuit designs.

Unregulated power supply output variations

As just mentioned, the DC output voltage of unregulated power supplies varies. That is, the output voltage goes up and down. This is due to either: a) variations in load resistance; and/or b) variations in mains (or "line") voltage.

Load variations

Recall that the output of a loaded DC power supply always contains some ripple voltage, the size of which determines the power supply's effective DC output voltage. Recall also that the amount of ripple is determined by the filter capacitor's value and the load's resistance. This means that if the load's resistance changes, the size of the ripple and the effective DC output voltage change also.

Importantly, this is a very real problem because, during the normal operation of most electronics equipment, the load resistance usually does change. To give you just one example of how, consider what happens when you turn the volume up on a domestic hi-fi. To output more sound, the speakers must draw more current which they do via the hi-fi (specifically, via its power amp stage). To facilitate this, the resistance of the hi-fi's power amp stage must drop which reduces the total resistance that the hi-fi presents to its power supply.

Line variations

Recall that a power supply's output is a function of several factors starting with its input voltage. If the input voltage changes, the power supply's output voltage must change also.

Importantly, this is a very real problem too because the input to most power supplies is mains which is an unregulated supply. That is, although mains is quoted at 240V RMS, technically is 230V in most states including NSW and is allowed to vary to as low as 216.2V and as high as 253V.

To appreciate the effect of this allowable variation, consider the example of a simple unregulated, unloaded half-wave rectifier in Figure 1a on the next page. With a mains voltage of 240V and a transformer turns ratio of 20:1, the secondary voltage is 12V RMS (so, 17Vpk) and the supply's maximum output voltage is 16.4V.

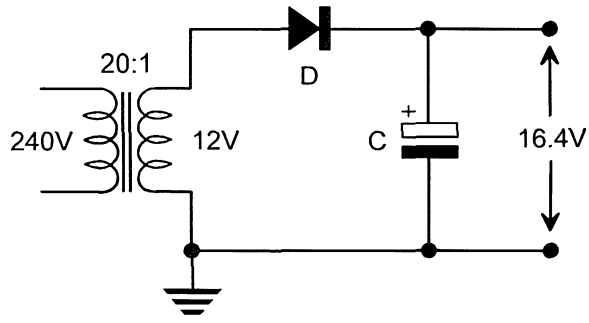

Figure 1a *With a mains of 240V the maximum output voltage is 16.4V*

However, as mains is permitted to vary from 216.2V to 253V, this means that the circuit's maximum output voltage can be anything between 15.5V to 17.3V. This is shown in Figures 1b and 1c.

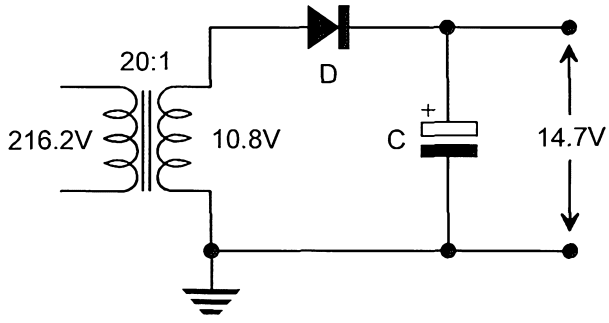

Figure 1b *With a mains of 216.2V the maximum output voltage is 14.7V*

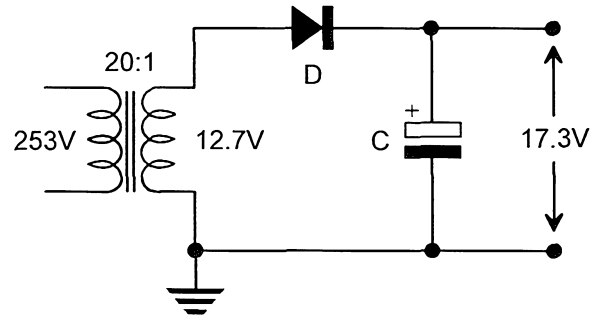

Figure 1c *With a mains of 253V the maximum output voltage is 17.3V*

Clearly, there is a need for an additional circuit to help keep the output voltage constant for variations in line and load. This is the function of the regulator.

What is a regulator?

A definition for the term *regulate* is, "to fix the amount or rate of something". That being the case, a *regulator* is something that manages the task of fixing the amount or rate of something.

You have probably seen regulators before. A gas cylinder for a barbecue has a regulator connected to the outlet valve to control the rate that the gas leaves the cylinder. If there wasn't a regulator connected all of the gas would rush out in a matter of seconds once the valve was opened. Another example is a pacemaker. The pacemaker ensures that a person's heartbeat occurs at regular intervals so it's basically a heartbeat regulator.

In the context of power supplies, a regulator is a device (or circuit) that is connected to the output of a filtered rectifier circuit that keeps the DC output voltage of a power supply as constant as possible for changes in the mains voltage (line regulation) and changes in the load resistance/current (load regulation).

There are two basic methods of connecting a regulator: either in parallel (or "shunt") with the load or in series with the load. This gives:

- shunt regulation; and
- series regulation

In both cases, the unregulated circuit must start with an effective DC output voltage that is at least 2V bigger than the required regulated DC output voltage (in some cases, more than 2V is necessary). This difference acts as a kind-of buffer that the regulator uses to help keep the output voltage constant. This is shown in Figure 2 below with the block diagram of a 10V regulated power supply.

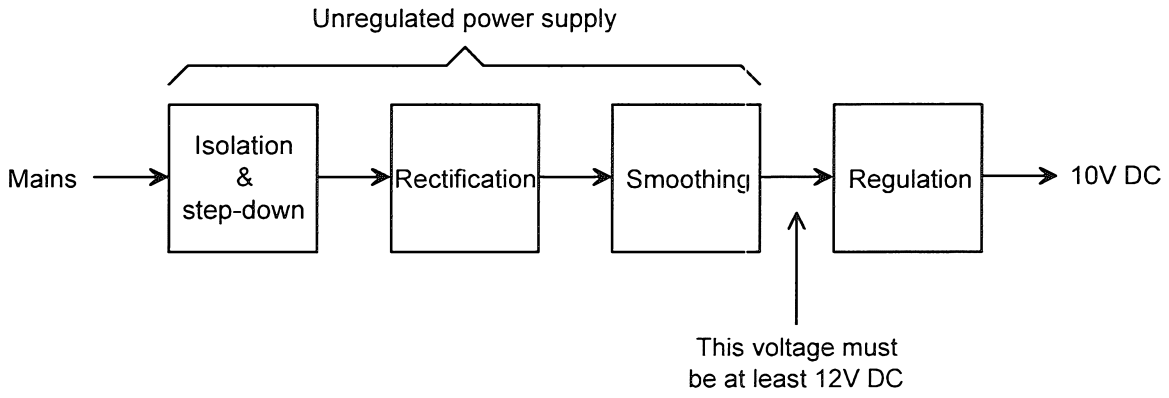

Figure 2 *The unregulated power supply's output voltage must be at least 2V bigger than the regulated output voltage*

The shunt regulator

Figure 3 below shows a filtered bridge rectifier connected to a load via a shunt regulator. Notice that the regulating device is connected in parallel (or shunt) with the load which gives this type of regulation its name.

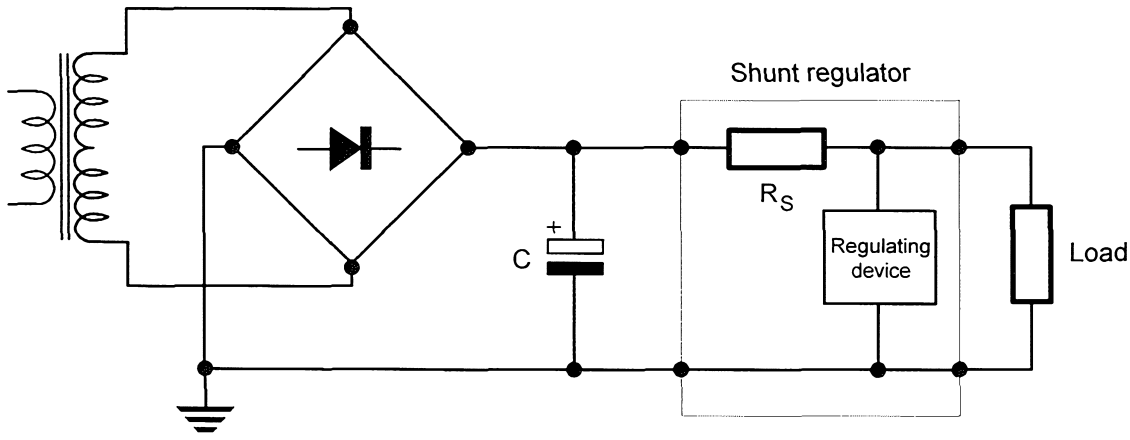

Figure 3 *The regulating device of a shunt regulator is connected in parallel with the load*

The shunt regulator keeps the output voltage constant by keeping the potential difference across itself constant despite changes in the line voltage or the load resistance. The zener diode is commonly used as a shunt regulator and its operation is explained in the next section.

The series regulator

Figure 4 below shows a filtered bridge rectifier connected to a load via a series regulator. Notice that the regulating device is connected in series with the load which gives this type of regulation its name.

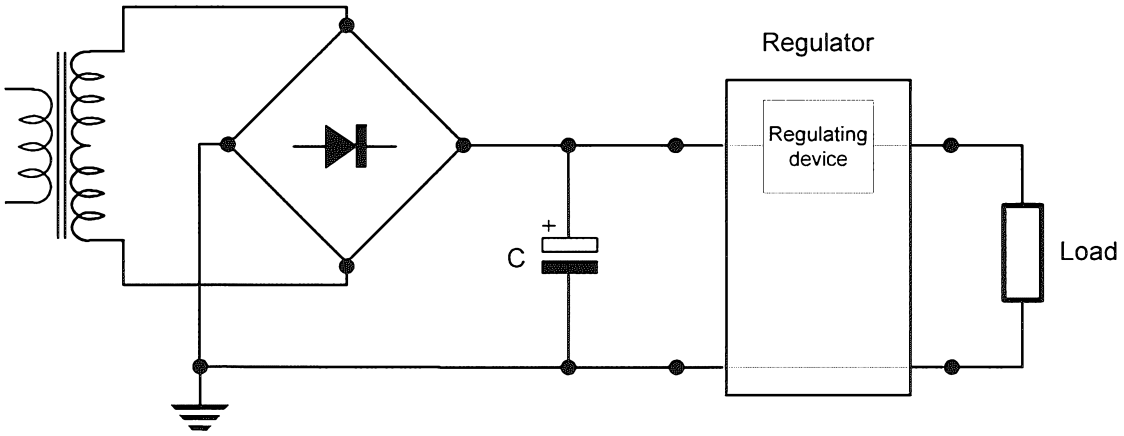

Figure 4 *The regulating device of a series regulator is connected in series with load*

The series regulator keeps the output voltage constant by actively varying the potential difference across itself. The 3-terminal regulator is a commonly used series regulator and its operation is explained in Section 8.

Quantifying load and line regulation

As already mentioned, regulator circuits attempt to keep the voltage out of a DC power supply as constant as possible for changes in line voltage (line regulation) and for changes in load resistance (load regulation).

Some power supplies are better than others at doing this. Consequently, there needs to be a method of measuring and quantifying line and load regulation so that we can compare the performance of power supplies (we wouldn't want to buy a dud!).

Load regulation

Load regulation is measured and quantified in the following way:

1. Measure the power supply's unloaded output voltage ($V_{no\text{-}load}$).

2. Measure the power supply's output voltage at the highest current it can supply to a load and still have a regulated output voltage ($V_{full\text{-}load}$). (Note: The full-load current is specified by the manufacturer.)

3. Plug these measurements into the equation below and solve:

$$Load\ regulation = \frac{V_{no\text{-}load} - V_{full\text{-}load}}{V_{full\text{-}load}} \times 100$$

The result is a number that tells us how much the output voltage will change (from no-load to full-load) as a percentage of the full-load output voltage. The better the power supply, the lower the load regulation figure.

To give you some idea about typical figures, the load regulation of a computer power supply costing $30 is about 5%. The load regulation of a laboratory power supply (like the ones in the classroom) which costs hundreds of dollars is 0.02%.

To demonstrate how to use the equation, let's do an example. A 15V power supply has a full-load current rating of 1A. At full load current, the supply's output voltage is measured at 13.7V. What is the supply's load regulation?

$$Load\ regulation = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100$$

$$Load\ regulation = \frac{15V - 13.7V}{13.7V} \times 100$$

$$Load\ regulation = 9.5\%$$

Practise using the equation by trying the following questions for yourself.

1. A 30V power supply has a full-load current rating of 3A. At full load current, the supply's output voltage is measured at 29.5V. What is the supply's load regulation?

2. What will be the output voltage at full load current of a 120V power supply if it's load regulation specification is 3%?

Line regulation
Line regulation is measured and quantified in the following way:

1. Measure the power supply's output voltage for the maximum mains voltage ($Vout_{(max)}$). [**Note:** Mains varies by ±5% which is 240V ±12V.]

2. Measure the power supply's output voltage for the minimum mains voltage ($Vout_{(min)}$).

3. Plug these measurements into the equation below and solve:

$$Line\ regulation = \frac{Vout_{(max)} - Vout_{(min)}}{Vout_{(nominal)}} \times 100$$

The result is a number that tells us how much the output voltage will change for changes in mains as a percentage of the supply's stated (nominal) output voltage. Again, the better the power supply, the lower the figure.

This method of quantifying line regulation can give different values depending on the supply's load current. That is, measuring and using the supply's maximum and minimum output voltages at no-load will give a different figure for line regulation compared to measuring and using the maximum and minimum output voltages at full-load (and any point in between).

Unfortunately, there isn't an industry standard regarding the level of current that should be used and so manufacturers use whatever load current they deem fit. This lack of an accepted standard means that values for line regulation cannot be fairly compared (unless the level of load current is specified). As a result, this information is of limited use and you're not expected to recall or use this equation in the tests.

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Remote sensing

The unit of competence makes a reference to a concept called "remote sensing". This is a design practice for regulated power supplies with resistive connections to the load.

To explain, although a power supply's output may be regulated at a particular value (say, 10V), long and/or thin conductors that connect to the load to the power supply can have sufficient resistance to develop a potential difference. As these conductors are connected in series with the load, Kirchhoff's Voltage Law tells us that this must have the effect of reducing the potential difference across the load (to, say, 9.7V). Moreover, as the potential difference across the conductors will vary with load current, the load voltage also effectively becomes unregulated.

Remote sensing solves this problem by using additional circuitry to enable the power supply to sense the potential difference across the load instead of across its output. The power supply then responds to drops in load voltage caused by this problem by increasing its output voltage until the load voltage is the correct value.

Skill practice 6

Practice measuring the output voltage and load current of unloaded and loaded unregulated power supplies (to obtain reference data for load regulation comparisons with shunt and series regulated power supplies)

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1 hour to complete this exercise.

Equipment

- 15V AC power supply
- prototyping panel
- decade box
- two DMM
- W04 bridge rectifier
- 100Ω 5W resistor
- 1000µF 63V electrolytic capacitor
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the breadboard.

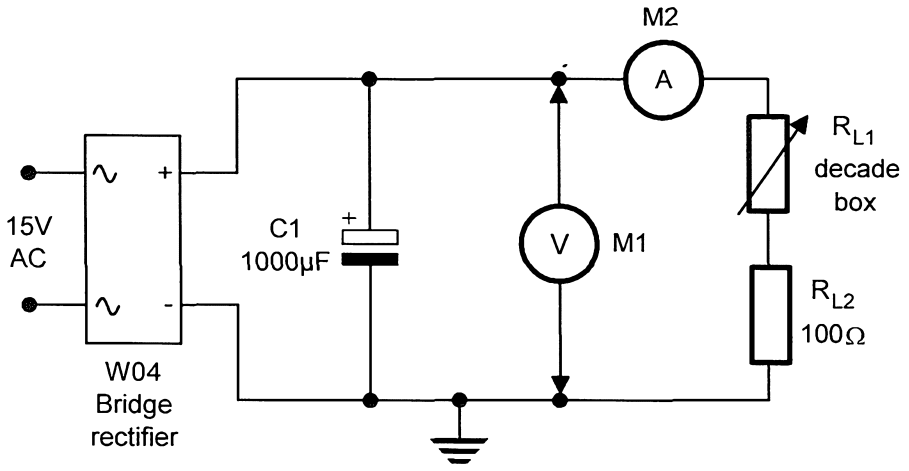


Figure 1

4. Read the brief circuit description below before proceeding.

Circuit description

The W04 is a device that contains four diodes to make a bridge rectifier and so it is providing the rectification.

The load resistance is being provided by the series combination of R_{L1} and R_{L2}. R_{L1} is a decade box which is basically a variable resistor. R_{L2} is in the circuit so that the total load resistance cannot be set lower than 100Ω (to protect the bridge rectifier).

M1 is being used to measure the effective DC output voltage from the power supply. Put another way, it is measuring the potential difference across the load.

M2 is being used to measure the load current.

5. Set the decade box's resistance for 2.4kΩ then turn on the AC power supply.

   Self check: If your circuit is working correctly, you should measure an output voltage of about 25V (on M1) and a load current of about 9mA (on M2). If you don't measure these values turn off the AC power supply immediately and check your wiring.

6. Disconnect the load from the circuit by disconnecting one of the wires to the decade box.

7. Measure the output voltage. Record your measurement in the first row of Table 1.

8. Reconnect the load.

9. Adjust the decade box's resistance until the load current is 10mA.

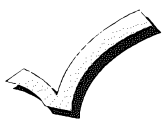
10. Measure and record the output voltage.

11. Repeat steps 9 and 10 for all the values of load current listed in Table 1.

12. Once the table is full, turn off the circuit.

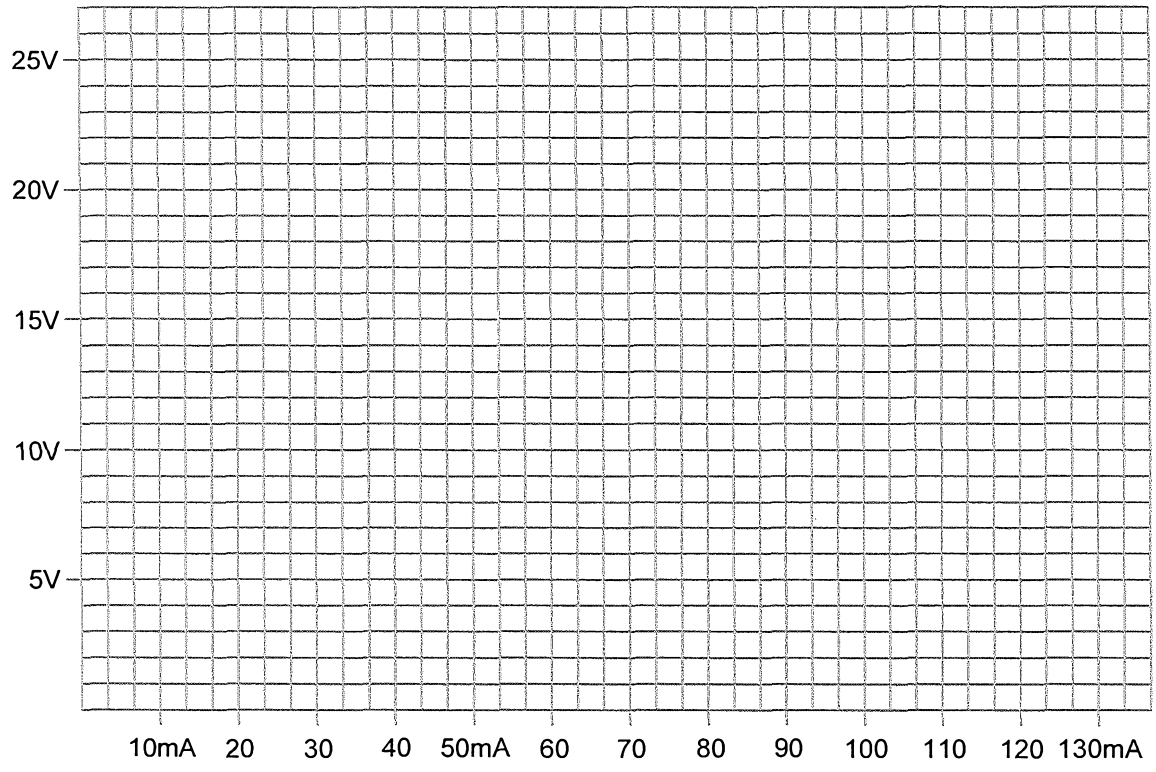
Table 1

Load current	Output voltage	Load current	Output voltage
0mA		70mA	
10mA		80mA	
20mA		90mA	
30mA		100mA	
40mA		110mA	
50mA		120mA	
60mA		130mA	



The teacher needs to check your work at this point...

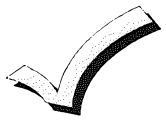
13. Draw a graph of load current versus load voltage on the graph below.



Question 1
What is the relationship between load current and load voltage?

Question 2
Why is the fall in output voltage with a rising output current a problem?

Question 3
In what way would your results in Table 1 and the graph be different if the same test is performed on a regulated power supply?



The teacher needs to check your work at this point...

14. Although this power supply is unregulated, the equation for calculating the load regulation can still be applied to your results. Calculate the circuit's load regulation percentage for the 40mA load current using the equation: $Load\ regulation = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100$. Record this figure in Table 2 below.

    Note: $V_{no-load}$ is the circuit's output voltage when the load current is zero. $V_{full-load}$ is the output voltage at 40mA.

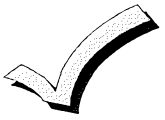
15. Repeat step 14 for the other load currents listed in the table.

Table 2

Load current	Load regulation %
40mA	
60mA	
80mA	
100mA	

Question 4
Why is the load regulation figure getting worse the higher the output current?

Question 5
In what way would your results in Table 2 be different if the same calculations were performed on a regulated power supply?



The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. The output voltage of an unregulated power supply

   ☐ increases as the load resistance decreases.
   ☐ is constant despite changes in load resistance.
   ☐ decreases as the load resistance decreases.
   ☐ decreases as the load resistance increases.

2. What is line regulation?

   _____

   _____

   _____

3. What is load regulation?

   _____

   _____

   _____

4. Name the two types of regulator circuit design.

   _____

   _____

5. Shunt regulation attempts to hold the load voltage constant for changes in

   ☐ line voltage.
   ☐ load current.
   ☐ line voltage and load current.
   ☐ temperature.

6. Series regulation attempts to hold the load voltage constant for changes in

- ☐ line voltage.
- ☐ load current.
- ☐ line voltage and load current.
- ☐ temperature.

7. Calculate the load regulation of a 12V power supply that is measured as having an output voltage of 11.6V at full-load current.

8. What is the output voltage of a 12V power supply with a load regulation specification of 7% at full load current?

Section 7 The zener diode shunt regulator

Purpose To develop your ability to use test equipment to test zener diode shunt regulator circuits, recognise when the circuit is faulty, and identify the likely faulty component.

Objectives At the end of this section you should be able to:

- Draw the schematic symbol for a zener diode
- Name and identify the terminals of a zener diode
- Interpret the graph of the potential difference versus current characteristic of typical zener diodes
- Describe the similarities and differences between zener diodes and rectifier diodes in terms of their reverse breakdown voltage, reverse leakage current, forward voltage and maximum forward current
- List typical values for the reverse breakdown voltage of commercially available zener diodes
- Draw the schematic diagram of a zener diode shunt regulator circuit
- Explain the operation of a zener diode shunt regulator circuit
- Determine the output voltage of a zener diode shunt regulator circuit given the unregulated DC input voltage and the zener diode's reverse breakdown voltage
- Calculate the current through, and the power dissipated by, the components in a zener diode shunt regulator given the unregulated DC input voltage and the zener diode's reverse breakdown voltage
- Conduct tests on zener diodes to identify the terminals and determine whether or not they are faulty
- Measure the output voltage of loaded shunt regulator power supply circuits using a DMM and an oscilloscope

Introduction

Section 6 of this workbook introduced you to the concept of regulation and why it is necessary in power supplies. Recall that there are two types of regulator circuits: shunt and series. This section explains the basic operation of a shunt regulator circuit.

A component crucial to the shunt regulator's operation is the *zener* diode. To understand how the shunt regulator works, you must first understand the zener diode's operation.

The zener diode

The schematic symbols used to represent the zener diode is shown in Figure 1 below.

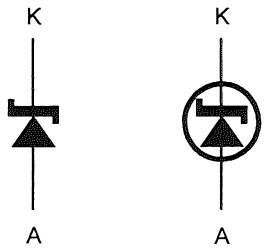


Figure 1 *Schematic symbols used to represent zener diodes*

The basic principle of operation of the zener diode is identical to that of the rectifier diode. When forward biased by approximately 0.6V (the actual voltage can range from 0.5V to 0.7V) the diode conducts current in the forward direction (that is, from anode to cathode).

And, when reverse biased, only leakage current flows until the reverse bias voltage exceeds the zener diode's reverse breakdown voltage (also known as the *avalanche* or *zenering* voltage). When this happens, the diode conducts current in the reverse direction (that is, from cathode to anode).

The fact that the basic principle of operation of the zener diode is the same as the rectifier diode means that the graph of anode-cathode voltage versus anode-cathode current of the rectifier diode also describes the zener diode's operation. This graph is shown in Figure 2 below.

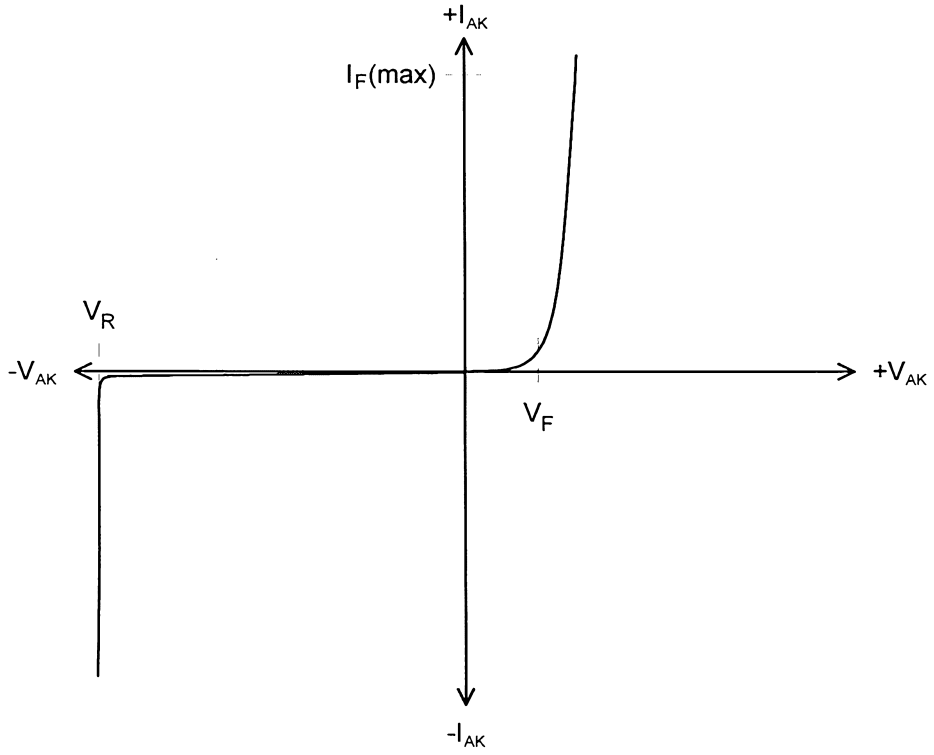


Figure 2 *The graph of anode-cathode voltage versus anode-cathode current for the zener diode*

So, what's the difference between a rectifier diode and a zener diode? The answer to this question is, the size of the rated reverse breakdown voltage. Rectifier diodes are manufactured to have a large reverse breakdown voltage (the higher the value the better). This is because it is not desirable for the diode in rectifier circuits to conduct in the reverse direction. If they did, there would be no rectification.

However, for the purpose of shunt regulation, it is necessary for zener diodes to conduct in the reverse direction. For this reason, zener diodes have much lower values of reverse breakdown voltage. Zener diodes are readily available with one of the following reverse breakdown voltages: 3.3V, 3.9V, 4.7V, 5.1V, 5.6V, 6.2V, 6.8V, 7.5V, 8.2V, 9.1V, 10V, 12V, 15V, 16V, 18V, 20V, 24V, 30V and 33V. Other voltages are available but you would need to check the manufacturer's data of specific devices to find out more.

The reason the reverse bias mode of zener diodes is useful can be understood if we closely examine the lower left-hand side of the graph of anode-cathode voltage versus anode-cathode current (shown in Figure 3 below). Notice that, once the line on the graph starts dropping down, it does so almost vertically. This means that, once the diode conducts current in the reverse direction, the potential difference across itself stays fairly constant. This is true regardless of the amount of reverse current though the diode as emphasised in Figure 3 below.

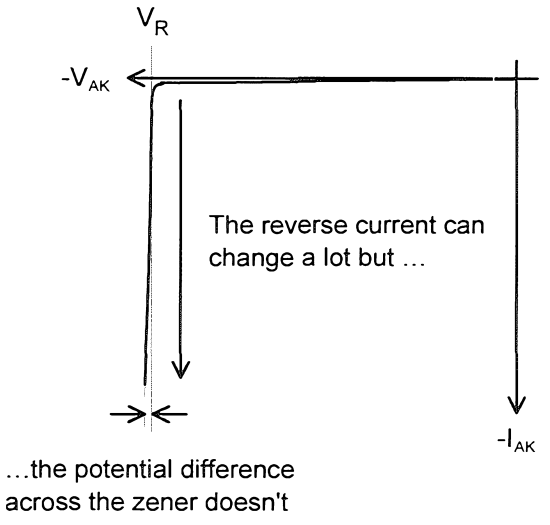


Figure 3 *The reverse bias potential across a diode is fairly constant*

In other words, diodes are natural regulators. And zener diodes are designed to take advantage of this effect by having it occur at the kinds of output voltages typically required of power supplies.

The zener diode shunt regulator

Figure 4 below shows the circuit of a zener diode shunt regulator connected between the output of a bridge rectifier (with smoothing) and a load.

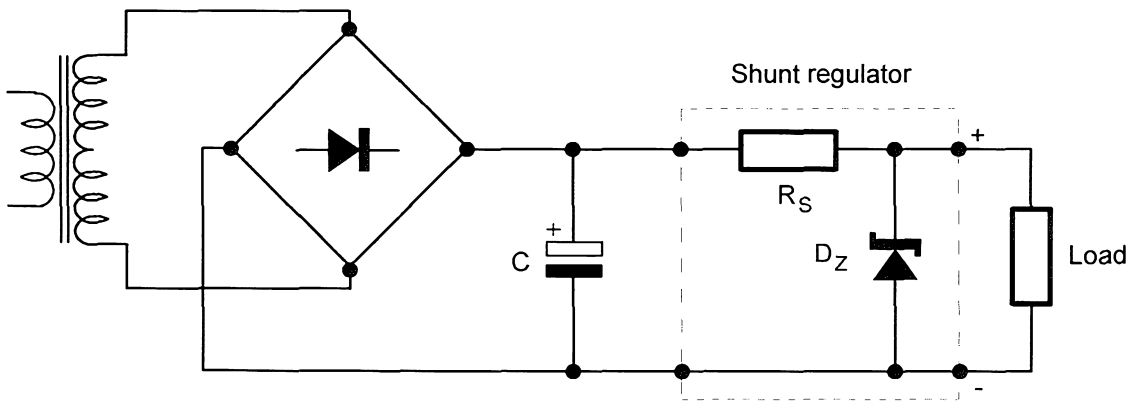


Figure 4 *The circuit of a shunt regulator connected between the output of a bridge rectifier (with smoothing) and a load*

The regulated DC output voltage of this circuit (and the voltage across the load) is set by the zener diode's rated zenering voltage. To explain, the zener diode is connected in parallel with the load and you may recall that the voltage across a parallel network is always the same. That being the case, the potential difference across the zener diode and the load must be the same. Crucially, the zener diode is connected so that it is reverse biased (that is, the diode's cathode is negative with respect to its anode). So, when the zener diode conducts current in the reverse direction, its potential difference and hence the voltage across the load is the zener diode's rated zenering voltage. Figure 5 below shows an example of this using a 5V zener diode.

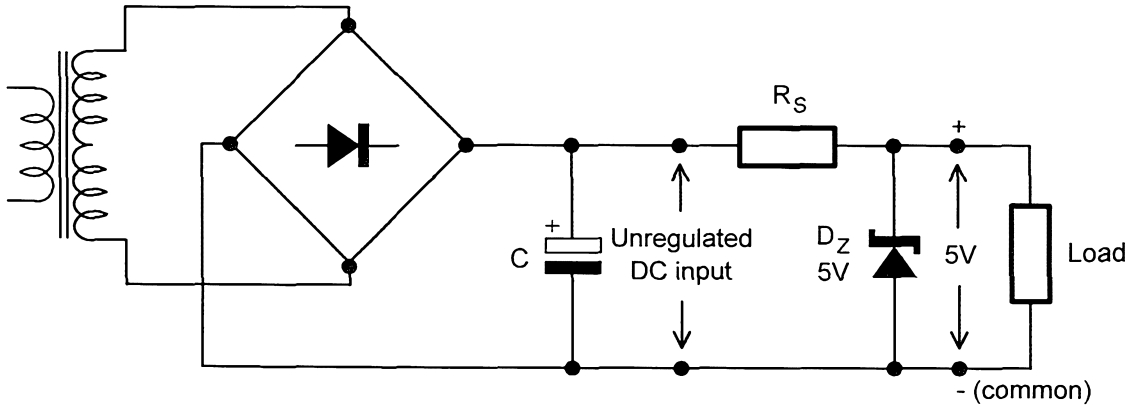


Figure 5 *The output voltage of the shunt regulator will be the same as the diode's rated zenering voltage*

The circuit regulates the output voltage (that is, keeps it fairly constant) because, as we have seen, the potential difference across a reverse biased diode, once it conducts current, is fairly constant regardless of the current's size.

Figure 6 below shows the current paths in the zener diode shunt regulator circuit.

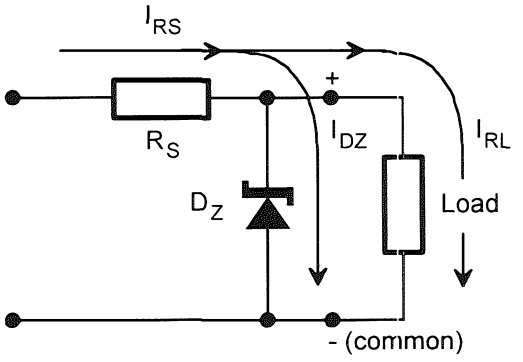


Figure 6 *The current paths in the zener diode shunt regulator circuit*

There are a couple of important points to make about the currents in the zener diode shunt regulator. First, according to Kirchhoff's Current Law (KCL), the current through the series resistor (I_{RS}) is the sum of the currents through the zener diode (I_{DZ}) and the load (I_{RL}).

Second, as the potential difference across the series resistor (V_{RS}) remains fairly constant (a point that will be explained shortly), the current through it (I_{RS}) also remains fairly constant.

Third, if we combine these two facts, we can deduce that if the load current (I_{RL}) changes (due to changes in load resistance) then the zener diode's current (I_{DZ}) must also change. Importantly, if the load current goes up, the zener diode current goes down and vice versa. In this way, the relationship between the zener diode and load currents is like two ends of a seesaw.

Predicting the voltages, currents and powers around the circuit

As a technician, you'll be expected to be able to repair DC power supplies that include shunt regulator circuits. Recall that this involves comparing measured voltages around the circuit with what they should be. As such, you need to be able to predict the voltages around the circuit by calculation.

In addition to this, the resistor (R_S) or the zener diode sometimes have to be substituted with equivalents because the original part is no-longer available or is too expensive. To make a decision about whether or not a particular resistor or zener diode is an appropriate equivalent, the power that they dissipate in the circuit must be known. As such, you'll also need to be able to calculate the currents around the circuit of a shunt regulator and the power dissipated by the components.

1. The regulated DC output voltage ($Vout_{(DC\ regulated)}$)

   As already mentioned, the regulated DC output voltage is the same as the zener diode's zenering voltage:

$$Vout_{(DC\ regulated)} = V_{DZ}$$

2. The potential difference across the series resistor (V_{RS})

   The potential difference across any resistor is always equal to the difference in voltage on its two leads (as long as the voltages have been measured or calculated with respect to the same point in the circuit). As we know, one lead of the series resistor is connected to the shunt regulator's input and the other is connected to the shunt regulator's output. Once the voltages (with respect to common) at these two points in the circuit are known, the potential difference across the series resistor is simply the difference between them.

$$V_{RS} = Vin_{(DC\ unregulated)} - Vout_{(DC\ regulated)}$$

   There are a couple of important point to make about these voltages. First, to ensure good line regulation, the unregulated DC input voltage must be at least two volts bigger than the zener diode's rated zenering voltage. If the input voltage drops much below this, the zener diode will be starved of current, turn off and no-longer regulate the output voltage.

   Second, as we know, the regulated DC output voltage should remain fairly constant. That being the case, the potential difference across the series resistor will only change if the input voltage changes.

3. The current through the series resistor (I_{RS})

   If the potential difference across a resistor and the resistor's value are known the current through the resistor can be calculated using Ohm's Law. That being the case:

$$I_{RS} = \frac{V_{RS}}{R_S}$$

4. The current through the zener diode (I_{DZ})

   Finding the current through the zener diode is a two step process. First, the current through the load must be found:

$$I_{RL} = \frac{V_{RL}}{R_L}$$

   Once the current through the load is known, the current through the zener diode can be calculated by taking advantage of KCL:

$$I_{DZ} = I_{RS} - I_{RL}$$

5. The power dissipated by the series resistor (P_{RS})

   With the information available at this point, there are three ways of calculating the power dissipated by the series resistor. They are:

$$P_{RS} = I_{RS} \times V_{RS} \qquad P_{RS} = \frac{V_{RS}^2}{R_S} \qquad P_{RS} = I_{RS}^2 \times R_S$$

6. The power dissipated by the zener diode (P_{DZ})

   There is only one way to calculate the power dissipated by the zener diode:

$$P_{DZ} = I_{DZ} \times V_{DZ}$$

Let's do an example with a shunt regulator connected to the output of a half-wave rectifier.

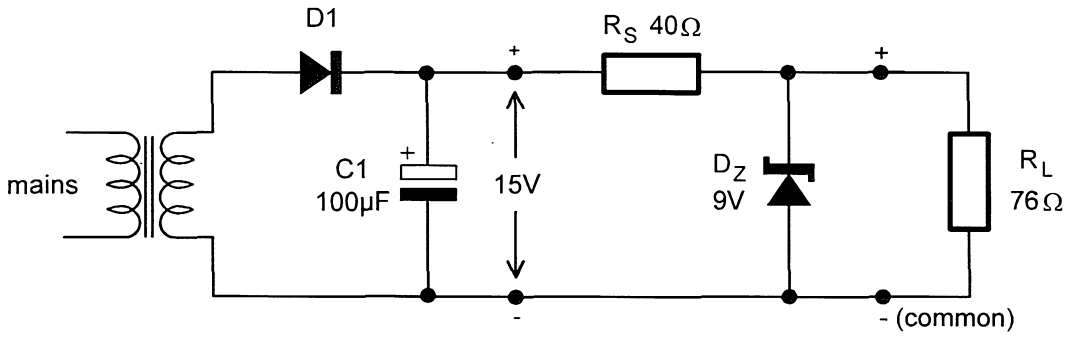


Figure 7

First, calculate the regulated DC output voltage.

$$Vout_{(DC\ regulated)} = V_{DZ}$$

$$Vout_{(DC\ regulated)} = 9V$$

Next, find the potential difference across the series resistor.

$$V_{RS} = Vin_{(DC\ unregulated)} - Vout_{(DC\ regulated)}$$

$$V_{RS} = 15V - 9V$$

$$V_{RS} = 6V$$

Then, find the current through the series resistor.

$$I_{RS} = \frac{V_{RS}}{R_S}$$

$$I_{RS} = \frac{6V}{40\Omega}$$

$$I_{RS} = 150mA$$

Next, find the current through the zener diode (remember, this is a two step process).

$$I_{RL} = \frac{V_{RL}}{R_L}$$

$$I_{RL} = \frac{9V}{76\Omega}$$

$$I_{RL} = 118.4mA$$

$$I_{DZ} = I_{RS} - I_{RL}$$

$$I_{DZ} = 150mA - 118.4mA$$

$$I_{DZ} = 31.6mA$$

Now the powers dissipated by the components can be found. First, the power dissipated by the series resistor.

$P_{RS} = I_{RS} \times V_{RS}$ or $P_{RS} = \frac{V_{RS}^2}{R_S}$ or $P_{RS} = I_{RS}^2 \times R_S$

$P_{RS} = 150mA \times 6V$ $P_{RS} = \frac{6V^2}{40\Omega}$ $P_{RS} = 150mA^2 \times 40\Omega$

$P_{RS} = 900mW$ $P_{RS} = 900mW$ $P_{RS} = 900mW$

Then the power dissipated by the zener diode.

$$P_{DZ} = I_{DZ} \times V_{DZ}$$

$$P_{DZ} = 31.6mA \times 9V$$

$$P_{DZ} = 284.4mW$$

Practise calculating the voltages and currents around the circuit of a zener diode shunt regulator and the power dissipated by the components by trying the following questions for yourself.

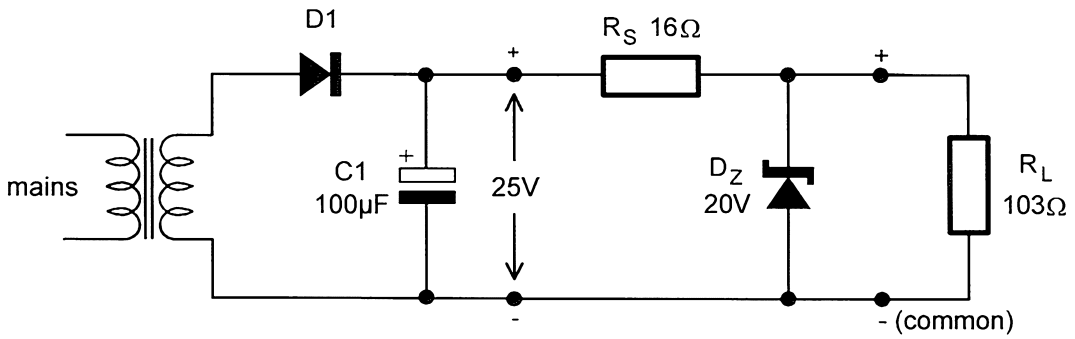


Figure 8

1. What is the regulated DC output voltage ($Vout_{(DC\ regulated)}$)?

2. Calculate the potential difference across the series resistor (V_{RS}).

3. Calculate the current through the series resistor (I_{RS}).

4. Calculate the current through the load resistor (R_L).

5. Calculate the current through the zener diode (I_{DZ}).

6. Calculate the power dissipated by the series resistor (P_{RS}).

7. Calculate the power dissipated by the zener diode (P_{DZ}).

8. Calculate the power dissipated by the load (P_{RL}).

Have your teacher check your answers to questions 1 to 8 before continuing.

9. What would happen to the current through the load if its resistance went down?

10. What would happen to the current through the zener diode if the load resistance went down?

Have your teacher check your answers to questions 9 and 10 before continuing.

11. How much current would flow through the zener diode if the load is disconnected?

12. How much power would the zener diode dissipate if the load is disconnected?

13. Would the power dissipated by the series resistor change if the load is disconnected? Explain your answer.

Fault-finding the shunt regulator

As there are only two components in the zener diode shunt regulator, there's not a lot that can go wrong. The following are some of the likely faults and the effect that they would on the circuit. These effects are shown on the circuit of a 12V zener diode shunt regulator with a 15V unregulated DC input voltage.

- R_S open-circuit

  If R_S goes open-circuit there is no electrical connection from input to output so the output voltage drops to zero. This is shown in Figure 9 below.

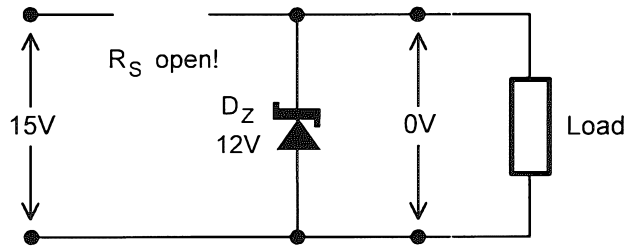


Figure 9

- D_Z open-circuit

  If D_Z goes open-circuit the output voltage is no-longer regulated and is a value less than 15V (the exact value depends on the load's resistance) because the load and R_S form a voltage divider. This is shown in Figure 10 below.

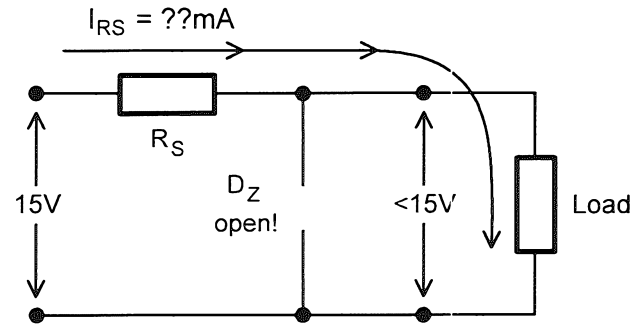


Figure 10

- D_Z short-circuit

  If D_Z goes short-circuit a dead-short is connected across the output/load and so it drops to zero. This is shown in Figure 11 below.

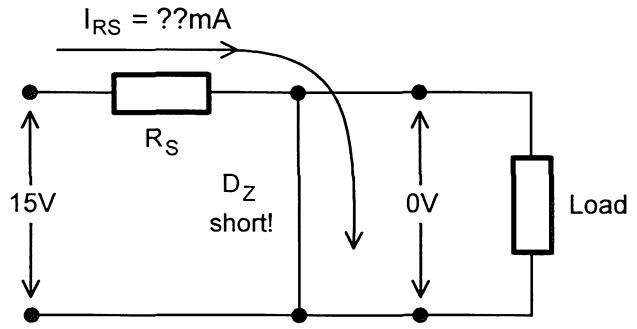


Figure 11

If you compare, you'll notice that the effects of this fault on voltages around the circuit are identical to the effects of R_S going open-circuit. To distinguish between the two faults you could check the temperature of R_S or the zener diode by touching them (carefully!). If either of them are warm then D_Z is short. If they're both cold then R_S is open

Ultimately, it's better not to try to simply remember a set of fault conditions and the effects they have on a particular circuit. This is true for all circuits, not just the shunt regulator or power supplies. There are just too many circuits with too many components each with multiple possible faults for this approach to work. Instead, it's much better to understand and remember how circuits work. This way, you can work out for yourself what the effects would be of a particular component failure.

Substituting components

Sometimes, when servicing equipment, you will be required to replace a faulty component that you don't have another one of at hand. Or sometimes, if the equipment is older, the faulty part may no-longer be available. In these situations you will have to choose a substitute that is a "best fit" for the job.

If the zener diode in a shunt regulator is faulty and a substitute is necessary, the substitute must have the same zenering voltage as the original part otherwise the regulated DC output voltage will be wrong. In addition, the power rating of any substitute must be as high as, or higher than, the original part. The teacher will show you examples of zener diode data sheets.

If R_S is faulty, any substitute must have the same resistance as the original part (or very, very close to it) otherwise the maximum full-load output current will be different (which may be a problem). In addition, the power rating of any substitute must be as high as, or higher than, the power rating of the original part.

Sometimes, the power rating of the original components may not be readily determined because the they can be so damaged that their physical size and hence their power rating is hard to guess. And sometimes, a recurring fault with one of the components can lead you to suspect that the power rating of the original part was too low in the first place. In these situations you'll need apply your knowledge of electronics theory to calculate an appropriate minimum power rating for any substitute.

Skill practice 7

Practise measuring the output voltage of loaded shunt regulator power supply circuits using a DMM and an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- 15V AC power supply
- prototyping panel
- decade box
- two DMMs (but no meter leads)
- W04 bridge rectifier
- 68Ω 5W resistor
- 100Ω 5W resistor
- 15V 1W zener diode (1N5352B)
- 1000µF 63V electrolytic capacitor
- BNC to alligator-clip lead
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the breadboard. Don't forget to link the circuit's common back to the earth terminal on the AC power supply.

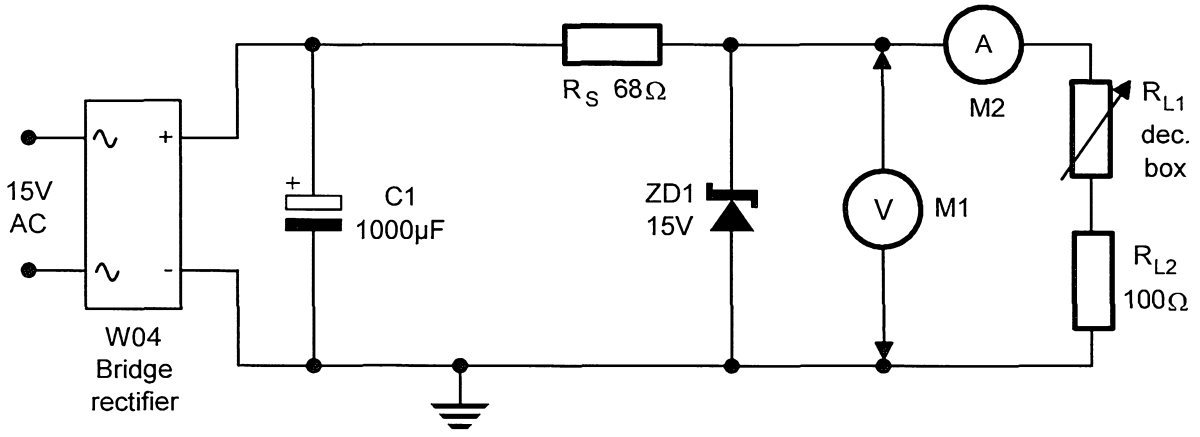


Figure 1

4. Read the brief circuit description below before proceeding.

Circuit description

The bridge rectifier and filter capacitor (*C1*) form the unregulated power supply (see Figure 2 on the next page).

R_S and D_Z form the shunt regulator circuit (see Figure 2 also).

The load resistance is being provided by the series combination of R_{L1} and R_{L2}.

M1 measures the regulated DC output voltage ($Vout_{(DC\ regulated)}$) from the power supply and M2 measures the load current (I_{RL}).

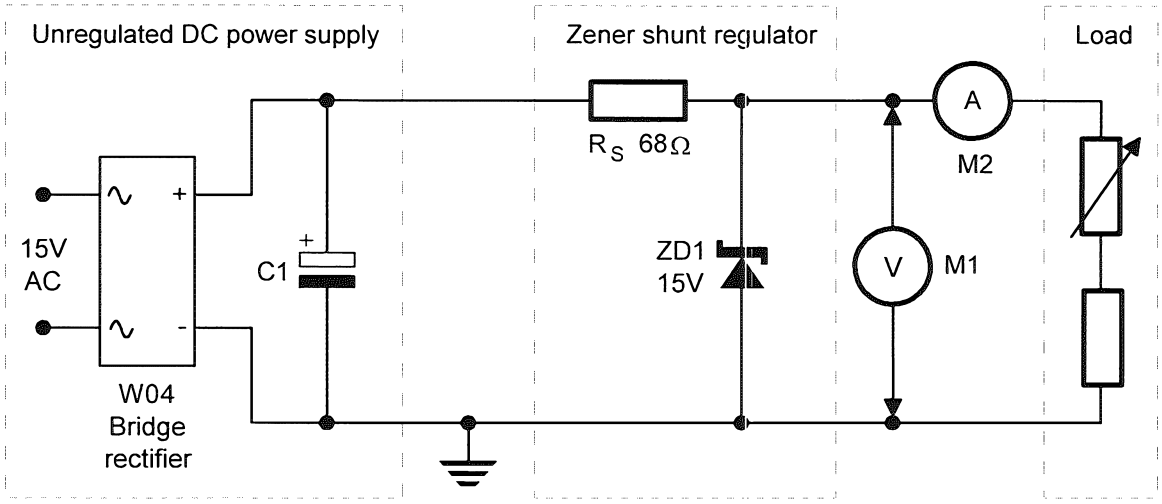


Figure 2

5. Set the decade box's resistance for 2.4kΩ then turn on the AC power supply.

   Self check: If your circuit is working correctly, you should measure an output voltage of about 15V (on M1) and a load current of about 6mA (on M2). If you don't measure these values turn off the AC power supply immediately and check your wiring.

6. Disconnect the load from the circuit by disconnecting one of the wires to the decade box.

7. Measure the regulated DC output voltage. Record your measurement in the first row of Table 1 (on the next page).

8. Reconnect the load.

9. Adjust the decade box's resistance until the load current is 10mA.

10. Measure and record the output voltage.

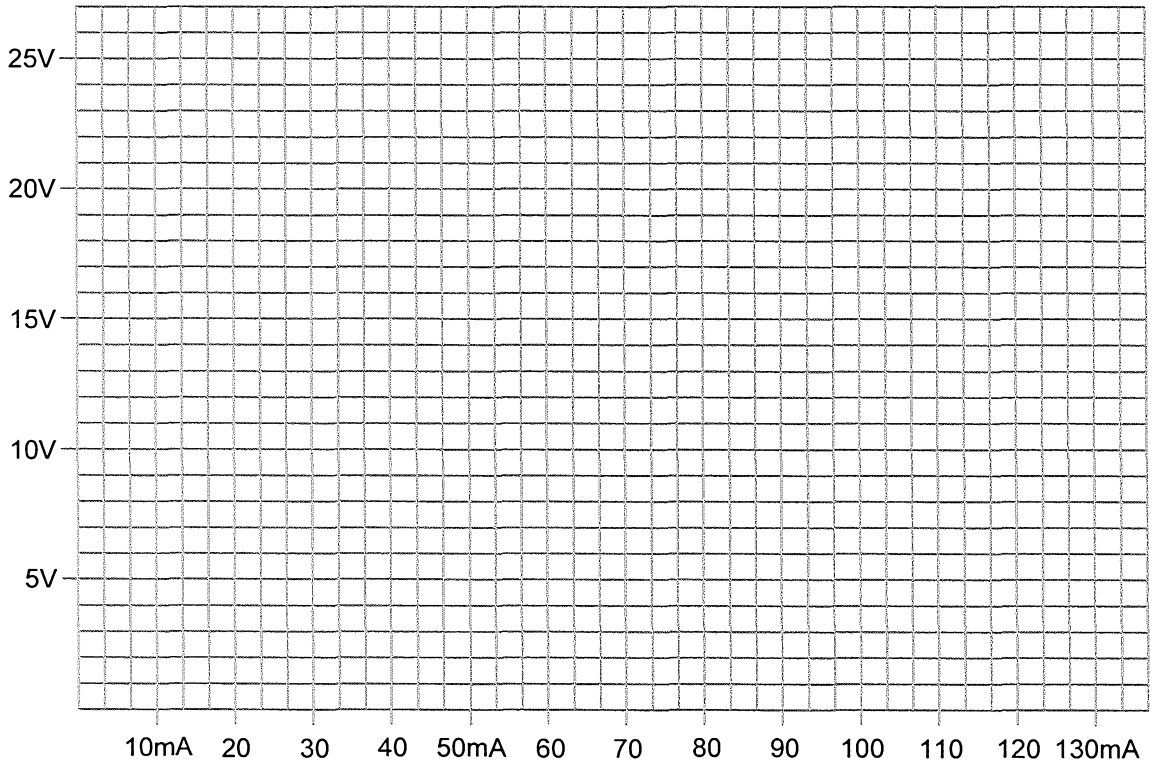
11. Repeat steps 9 and 10 for all the values of load current listed in Table 1.

12. Once the table is full, turn off the circuit.

Table 1

Load current	$Vout_{(DC\ regulated)}$	Load current	$Vout_{(DC\ regulated)}$
0mA		70mA	
10mA		80mA	
20mA		90mA	
30mA		100mA	
40mA		110mA	
50mA		120mA	
60mA		130mA	

13. Draw a graph of load current versus load voltage on the graph below.



Question 1
Why isn't the no-load output voltage exactly 15V?

Question 2
Compare this graph with the graphed results for the unregulated power supply in Skill Practise 6 (see page 6-15). What attribute makes this graph a better one?

The teacher needs to check your work at this point...

14. Calculate the circuit's load regulation percentage for the 40mA load current using the equation: $Load\ regulation = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100$. Record this figure in Table 2 below.

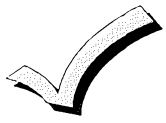
    Note: $V_{no-load}$ is the circuit's output voltage when the load current is zero. $V_{full-load}$ is the output voltage at 40mA.

15. Repeat Step 14 for the other load currents listed in the table.

Table 2

Load current	Load regulation %
40mA	
60mA	
80mA	
100mA	

Question 3
Compare the figures in Table 2 with the same figures for the unregulated power supply in Skill Practise 6 (see page 6-16). The zener diode shunt regulator has produced figures that are all better in what way?



The teacher needs to check your work at this point...

16. Adjust the decade box so the load current is 70mA.

17. Connect the CRO's channel 1 input across the output of the circuit power supply (connect the alligator-clips to the same points in the circuit as the voltmeter).

18. Measure the peak-to-peak ripple voltage across the load. Record your measurement in Table 3 below.

    Note: Make sure that the *Input Coupling* control for channel 1 on the CRO is set to *AC*.

19. Turn off the AC power supply.

20. Remove the zener diode.

21. Remove the 68Ω series resistor and replace it with a hook-up wire.

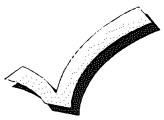
22. Turn on the AC power supply.

23. Measure and record the peak-to-peak ripple voltage across the load.

Table 3

Ripple with regulation	Ripple without regulation

Question 4
What is the added benefit of a power supply having a regulator circuit?



The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. Draw the schematic symbol of a zener diode.

2. Label the diode's terminals on your drawing above.

3. What is the main difference between a rectifier diode and a zener diode?

_____

_____

_____

4. What is the forward voltage drop across a zener diode?

_____

5. In what mode of operation are zener diodes usually operated?

☐ Forward biased

☐ Reverse biased

6. What is another name for the reverse breakdown voltage of a zener diode?

_____

_____

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Questions 7 and 8 refer to the circuit in Figure 1 consisting of a 4.7V zener diode

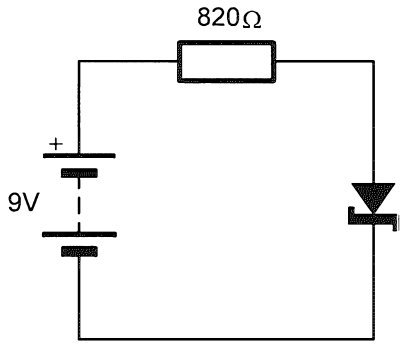

Figure 1

7. What is the potential difference across the zener diode?

_____

8. What is the potential difference across the resistor?

_____

_____

_____

Questions 9 to 14 refer to the circuit in Figure 2 consisting of a 4.7V zener diode

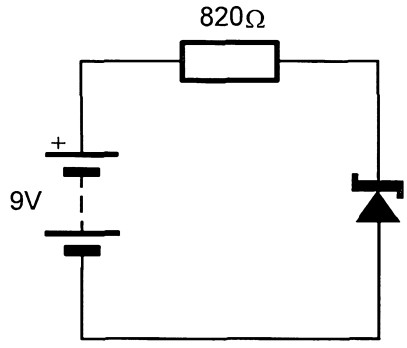

Figure 2

9. What is the potential difference across the zener diode?

10. What is the potential difference across the resistor?

11. What is the circuit current?

12. What is the power dissipated by the resistor?

13. What is the power dissipated by the zener diode?

14. What is the total power dissipated by the circuit?

Questions 15 to 27 refer to the circuit of Figure 3 below

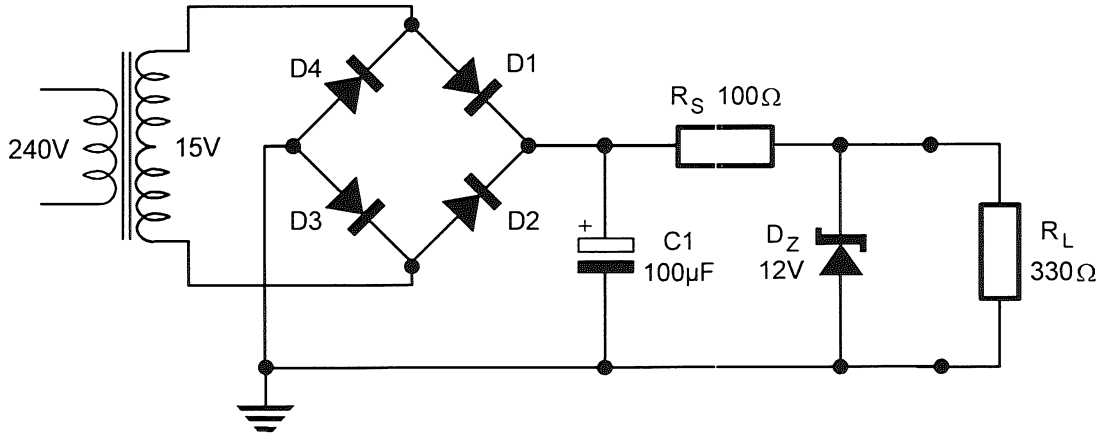

Figure 3

15. What is the potential difference across the load (V_{RL})?

16. What is the input voltage to the shunt regulator ($Vin_{DC\ unregulated}$)?

17. What is the potential difference across the resistor (V_{RS})?

18. What is the current through the resistor (I_{RS})?

19. What is the current through the load (I_{RL})?

20. What is the current through the zener diode (I_{DZ})?

21. What is the power dissipated by the load (P_{RL})?

22. What is the power dissipated by the zener diode (P_{DZ})?

23. What is the power dissipated by the resistor (P_{RS})?

24. What is the minimum allowable input voltage to the shunt regulator?

25. What would happen if the input voltage to the shunt regulator dropped below this voltage?

26. What is the most suitable power rating for the series resistor?

- ☐ ¼W
- ☐ ½W
- ☐ 1W
- ☐ 5W

27. What is the most suitable power rating for the zener diode?

- ☐ ¼W
- ☐ ½W
- ☐ ¾W
- ☐ 1W

Questions 28 and 29 refer to the circuit in Figure 4 below

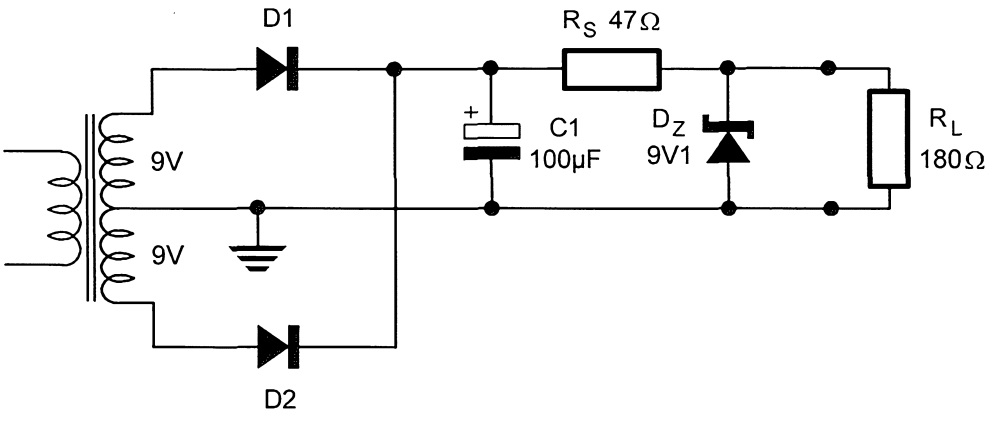

Figure 4

28. What is the potential difference across the load (V_{RL})?

29. What is the power dissipated by the zener diode (P_{DZ})?

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Student notes

Section 8 The 3-terminal regulator IC

Purpose To develop your ability to use test equipment to test 3-terminal IC regulator circuits, recognise when the circuit is faulty, and identify the likely faulty component.

Objectives At the end of this section you should be able to:

- Draw and label the schematic symbol of a 3-terminal regulator IC
- List three advantages of 3-terminal regulator ICs relative to zener diode shunt regulator circuits
- List the packages of common commercially available 3-terminal regulators
- Recognise series regulator circuits implemented using 3-terminal regulators
- Explain the purpose of the capacitors that are commonly connected across the input terminals and output terminals of 3-terminal regulators
- Define the term *dropout voltage*
- Identify the DC output voltage of common commercially available 3-terminal regulators given a part number
- Calculate the output voltage of a 3-terminal regulator circuit given the unregulated DC input voltage and the 3-terminal regulator's part number
- Calculate the current through, and the power dissipated by, the components in a 3-terminal regulator given the unregulated DC input voltage and the 3-terminal regulator's part number
- Predict the voltage on the output of the LM317 3-terminal regulator (for both fixed and variable outputs)
- Measure the output voltage of loaded 3-terminal regulator power supply circuits using a DMM

Introduction

Recall that the purpose of regulation is to keep the output voltage of a power supply constant despite changes in the load resistance or mains voltage. Recall also that there are two types of regulation: shunt and series. The last section examined the operation of the zener diode shunt regulator circuit. This section finishes off the topic by looking at an IC device that implements series regulation called the *3-terminal regulator*.

The 3-terminal regulator IC

The 3-terminal regulator IC is a remarkable device. It's actually a complex circuit that implements series regulation and so has excellent load regulation performance (for reasons not explained here). Series regulation is also more efficient than shunt regulation so 3-terminal regulator ICs waste less power. And finally, the circuit inside the IC provides is complex because it has been designed to provide additional benefits including (but not limited to): better line regulation performance and short-circuit protection. 3-terminal regulator ICs are so good and the price so relatively cheap that they are very widely used in power supplies.

The schematic symbol of a three terminal regulator is shown in Figure 1 below.

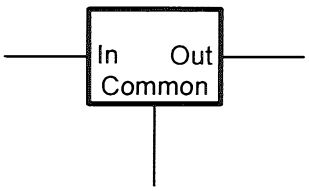


Figure 1 *The 3-terminal regulator*

Although the 3-terminal regulator is an IC, it's usually available in transistor packages such as the TO-92, TO-220 and TO-3 packages. They're also available in the TO-252 package. These are shown in Figure 2 below.

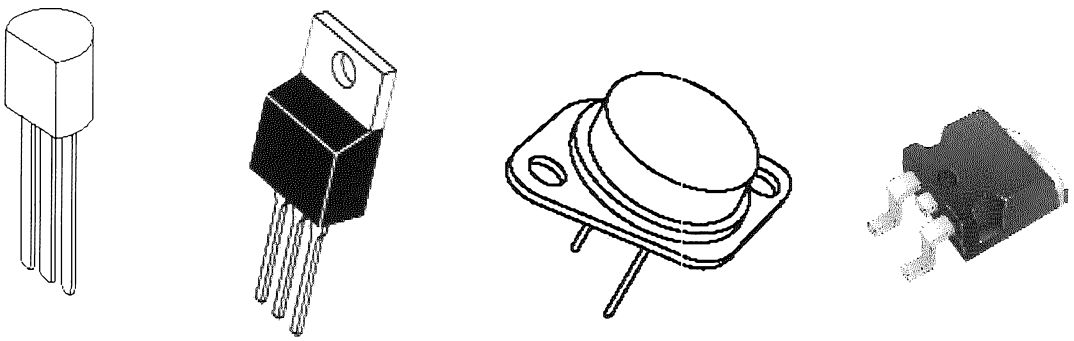


Figure 2 *From left to right: the TO-92; TO-220; TO-3; and TO-252 (or D^2PAK) packages*

The 3-terminal regulator is a complete series regulator. That is, it needs no other components to provide regulation in a DC power supply. Figure 3 below shows an example of a complete power supply with (series) regulation implemented using a 3-terminal regulator.

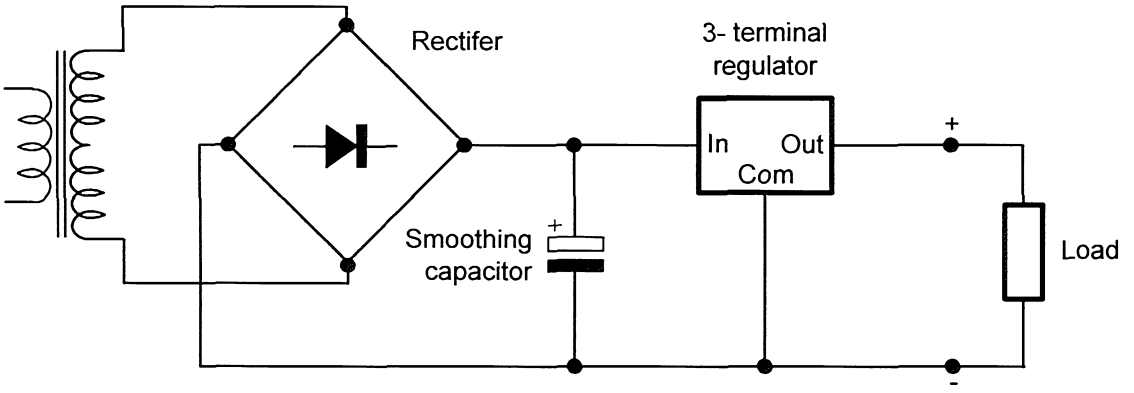


Figure 3 *The circuit of a series regulator implemented using a 3-terminal regulator connected between the output of a bridge rectifier (with smoothing) and a load*

Two capacitors are often added to the circuit and are connected as shown in Figure 4 below.

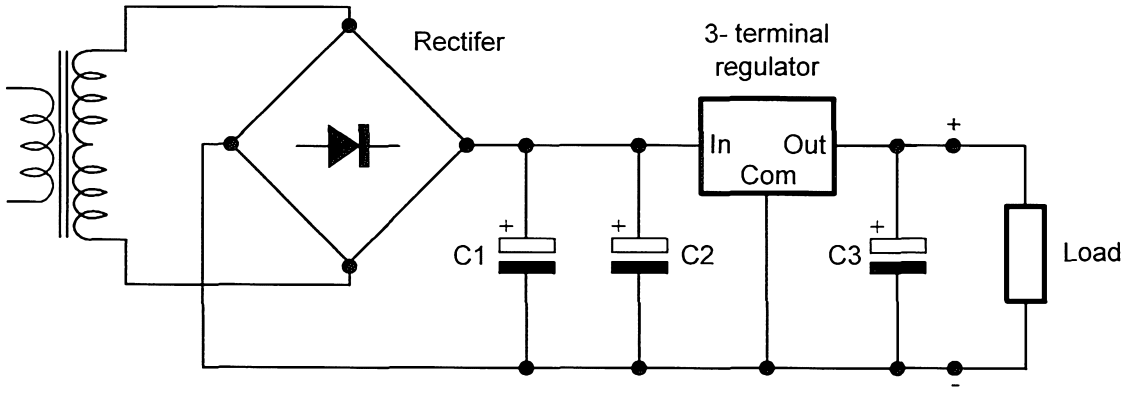


Figure 4 *Although external components are not necessary for 3-terminal regulators, capacitors are usually connected from the input and output terminals to common*

Capacitor *C2* is typically 100nF and is used to shunt noise to common. It's only usually included when the 3-terminal regulator cannot be physically mounted right next to the rectifier and smoothing capacitor. In this situation, the length of the PCB track to the regulator's input can be long enough to pick-up electrical noise that adversely affects the regulator's performance.

Capacitor *C3* is sometimes added to help improve the circuit's stability (that is, to help prevent it from oscillating at a high frequency) by ensuring that the gain of the circuit is 1 (one) at high frequencies. It can also shunt to ground any transients generated by the load from travelling back into the regulator's output which can adversely affect the regulator's performance and even damage it. Typical values for *C3* range from 100nF to 1µF and tantalum capacitors are regularly used.

Dropout voltage

To ensure that the 3-terminal regulator has sufficient current for its own needs, and to guarantee its ability to provide good line regulation, its input voltage must be bigger than its output voltage by a certain minimum amount.

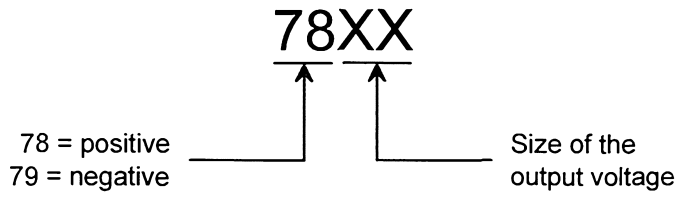
This minimum allowable difference between the input and output voltages is called the *dropout voltage*. For example, the minimum input voltage for a +22V 3-terminal regulator with a 2V dropout voltage rating is 24V. Below this value, the regulator's operation becomes unreliable.

Two common 3-terminal regulator ICs

Although there are many 3-terminal regulators, two that are widely used are: the 78/79 series and the 320/340 series.

The 78/79 series

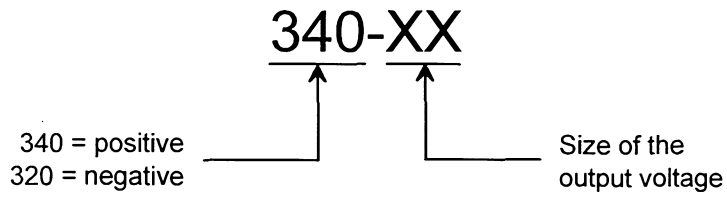
The part numbering system for these devices tells us about two of its key specifications: the polarity of the power supply that it can be used with and the size of its output voltage. Decoding of the part number is shown below.



For example, the 7805 is a +05V regulator and the 7912 is a -12V regulator.

The 340/320 series

The part numbering system for these devices is similar to the 78/79 series. Decoding of the part number is shown below.



For example, the 340-15 is a +15V regulator and the 320-05 is a -5V regulator.

Importantly, you must use the correct polarity 3-terminal regulation for the power supply. In other words, you cannot connect a 79XX or a 320-XX to the output of a positive rectifier. Similarly, you cannot connect a 78XX or a 340-XX to the output of a negative rectifier.

Predicting the voltages, currents and powers around the circuit

For reasons already explained in other sections, technicians are expected to be able predict the voltages, currents and powers around the circuit of a 3-terminal regulator by calculation.

1. The regulated DC output voltage ($Vout_{(DC\ regulated)}$)

   As already mentioned, the regulated DC output voltage is the same as the regulator's rated output voltage (which is usually decoded from the regulator's part number).

$$Vout_{(DC\ regulated)} = The\ regulator's\ rated\ output\ voltage$$

2. The regulator current (I_{Reg})

   As it's name implies the series regulator is connected in series with the load. That being the case, the regulator current (that is, the current that flows from it's input terminal to its output terminal) must be the same as the load current. So, to calculate the regulator current, the load current must be calculated and this is done by using Ohm's Law.

$$I_{Reg} = I_{RL} = \frac{V_{RL}}{R_L}$$

3. The power dissipated by the regulator (P_{Reg})

   Most of the power dissipated by a 3-terminal regulator is due to the current that flows through it from the input terminal to the output terminal. That being the case, the power dissipated by a regulator is:

$$P_{Reg} = I_{Reg} \times (Vin_{(Reg)} - Vout_{(Reg)})$$

Let's do an example with a 3-terminal regulator connected to the output of a half-wave rectifier.

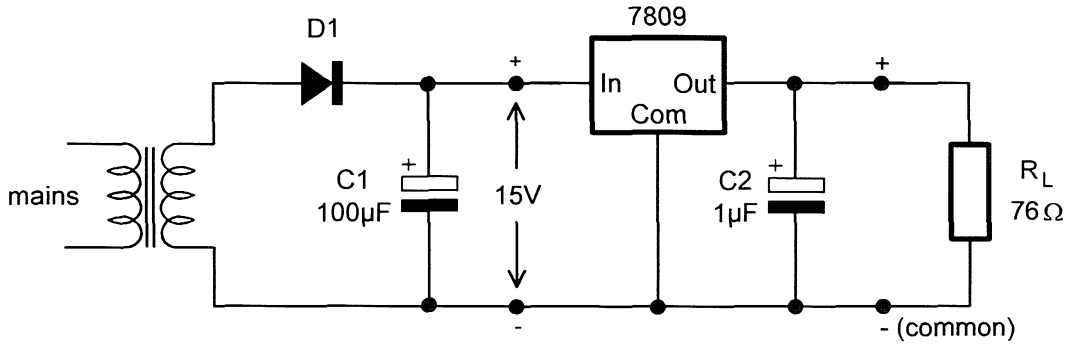


Figure 5

First, determine the regulated DC output voltage.

$$Vout_{(DC\ regulated)} = The\ regulator's\ rated\ output\ voltage$$

$$Vout_{(DC\ regulated)} = +9V$$

Then find the regulator current. Recall that this is done by finding the load current.

$$I_{Reg} = I_{RL} = \frac{V_{RL}}{R_L}$$

$$I_{Reg} = I_{RL} = \frac{9V}{76\Omega}$$

$$I_{Reg} = I_{RL} = 118.4mA$$

Finally, find the power dissipated by the regulator.

$$P_{Reg} = I_{Reg} \times (Vin_{(Reg)} - Vout_{(Reg)})$$

$$P_{Reg} = 118.4mA \times (15V - 9V)$$

$$P_{Reg} = 710mW$$

Practise calculating the voltages and currents around the circuit of a 3-terminal regulator circuit and the power dissipated by the components by trying the following questions for yourself.

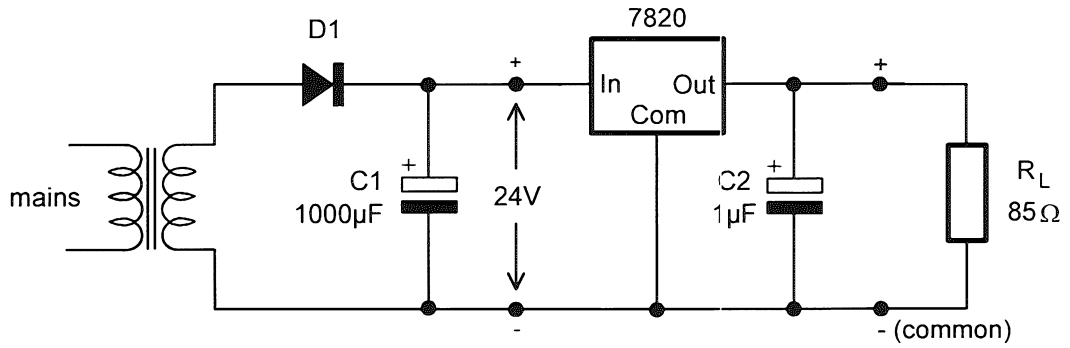


Figure 6

1. What is the regulated DC output voltage ($Vout_{(DC\ regulated)}$)?

2. Calculate the current through the regulator (I_{Reg}).

3. Calculate the power dissipated by the regulator (P_{Reg}).

4. Calculate the power dissipated by the load (P_{RL}).

5. What is the minimum allowable input voltage to the regulator if it has a dropout voltage rating of 2.5V?

Have your teacher check your answers to questions 1 to 5 before continuing.

6. Is *C1* a smoothing capacitor or a noise filtering capacitor? What tells you this?

7. What would happen to the current through the load if its resistance went down?

8. What would happen to the current through the regulator if the load resistance went down?

9. How much current would flow through the regulator if the load is disconnected?

10. How much power would the regulator dissipate if the load is disconnected?

Fault-finding 3-terminal regulators

Fault-finding these devices is pretty straight-forward in many respects. If there is an unregulated DC input voltage to the IC but no DC output voltage, or the output voltage is incorrect, then the regulator is probably faulty. If that's the case, the device is likely to be open-circuit or short-circuit between two of its three pins.

That said, there are a few traps to be alert to. First, the device must have a connection between its common pin and the circuit common for normal operation. A broken track or dry joint to this pin can make the regulator look faulty when it's not. Also, the capacitor connected across the regulator's output is usually a tantalum electrolytic type and these are notorious for going short-circuit.

Substituting 3-terminal regulators

The popularity of 3-terminal regulators is such that many devices have been available for over forty years and are likely to remain so for decades to come. That being the case, it is seldom difficult to obtain replacements for widely used devices. That said, one day an urgent repair or some other issue will force you to use a substitute.

The performance specification of a substitute 3-terminal regulator that **must** be matched to the original part is its output voltage. Using a regulator with a different output voltage to the original will, at best, cause the load to operate unreliably. At worst, one or more of the load's semiconductors will be damaged rendering it inoperable.

Other performance specifications that you may need to compare (in likely order) include:

- Maximum continuous current
- Maximum input voltage
- Dropout voltage
- Line regulation
- Load regulation

Maximum continuous current
This is the maximum current that the 3-terminal regulator's load is allowed to draw (because the load current passes through the device). If this figure is exceeded, the regulator risks being damaged.

Obviously, the substitute device should have a maximum continuous current rating equal to or better than the original part. If you can't obtain performance specifications for the original part, the device's package can give you a clue to its rating. The typical maximum continuous output current specification for common 3-terminal regulator packages are listed in Table 1. That said, these values may vary a little between devices using the same package so this can only be taken as a guide.

Table 1

Package	Maximum current
TO-92	100mA
TO-252 (or D^2PAK)	500mA
TO-220	1A
TO-3	3A

Maximum input voltage
This is the maximum allowable unregulated DC voltage that can be connected to the device's input terminal (a typical figure is 35V to 40V). Ideally, a substitute device should have a maximum input voltage that is equal to or greater than the original part's rated value. If the performance specifications of the original part are not available, choose a substitute with a rating that is greater than the circuit's unregulated DC voltage.

Dropout voltage
The typical drop-out voltage of most regulators including the 78 series is 2V. So, for example, the 7822 which has a +22V output must have an input of at least 24V for reliable operation. A substitute device should have a rated dropout voltage that is equal to or smaller than the original part's rated value. Again, if data on the original part is not available, choose a substitute with a rating that is smaller than the in-circuit difference between the device's input and output terminals (you'll probably find most devices satisfy this requirement).

Line and load regulation
It might surprise you to see these two specifications last. It's not that they're not important, it's just that the figures for these specifications of 3-terminal regulators are typically so good that you don't have to worry too much about them. Exceptions to this may include specialised equipment like measuring instruments, professional audio gear and medical equipment among others.

Internal 3-terminal regulator protection

3-terminal regulators are pretty sophisticated devices. Not only do they provide excellent line and load regulation, they also have three types of in-built protection which are listed below:

- Current limiting
- Thermal shutdown
- Safe-operating area protection

You're not expected to describe the operation of these protection mechanisms. However, it is worth knowing that, together, they provide excellent protection to the device in the event of short-circuit loads and make them virtually indestructible when used correctly.

External 3-terminal regulator protection

Although 3-terminal regulators are tough, they're prone to damage if a current is caused to flow the wrong way between to their *IN* and *OUT* terminals. This can happen when the regulator circuit comprises the two decoupling capacitors (*C2* and *C3*) and when *C2* fails and goes short-circuit. In this condition *C3* discharges to common via the regulator's *OUT* terminal (as shown in see Figure 7).

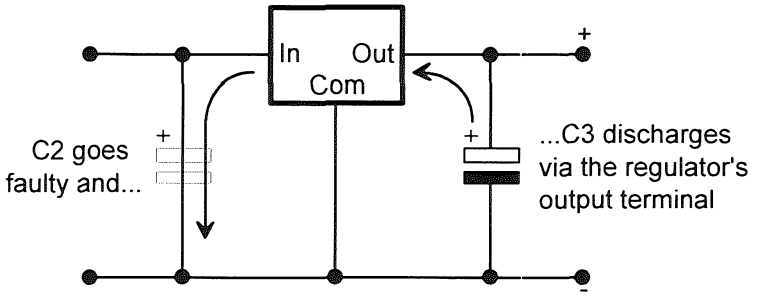


Figure 7 *An input short-circuit can damage a 3-terminal regulator by allowing the output decoupling capacitor to discharge through it*

To protect the regulator from this type of fault, a diode is simply connected between the input and output terminals in the polarity shown in Figure 8 below. In the no-fault condition, the regulator's input voltage is bigger than its output voltage and so the diode is reverse-biased and looks invisible to the circuit. But if *C2* goes short-circuit, *C3* discharges via the diode instead of the regulator (as long as the diode is fast-switching) protecting the IC from damage.

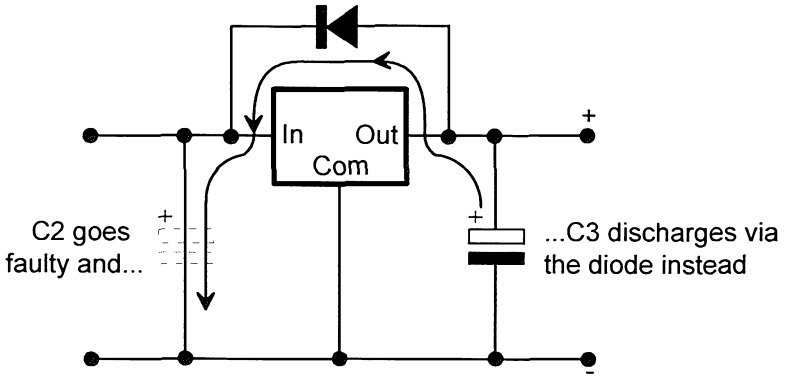


Figure 8 *If C2 goes short, C3 discharges via the diode, by-passing the 3-terminal regulator and protecting it from damage*

Programmable/variable output 3-terminal regulators

Some 3-terminal regulators are designed for output voltages that can be "programmable" or made variable. One such device that is widely used is the LM317. Figure 9 below shows the LM317 designed for an output voltage of 7.5V.

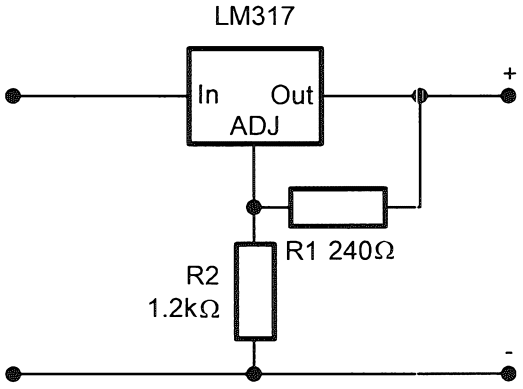


Figure 9 *The circuit using an LM317 3-terminal regulator*

The output voltage can be "programmed" by the selection of appropriate values for *R1* and *R2* and can be set to any voltage between 1.25V and 37V. The equation for calculating the output voltage for given values of resistance for *R1* and *R2* is provided by the manufacturer and shown below.

$$Vout = 1.25\left(\frac{R2}{R1} + 1\right) + 50\mu A \times R2$$

Let's use the equation to prove the circuit's output voltage.

$$Vout = 1.25\left(\frac{R2}{R1} + 1\right) + 50\mu A \times R2$$

$$Vout = 1.25\left(\frac{1k2\Omega}{240\Omega} + 1\right) + 50\mu A \times 1k2\Omega$$

$$Vout = 7.56V$$

Note: The manufacturers specify that *R1* should be a 240Ω resistor. However, the nearest E12 preferred resistor value is 220Ω and this can be used instead.

Modifying the LM317 circuit to obtain a variable output voltage is as simple as making *R2* a potentiometer wired as shown in Figure 10 below.

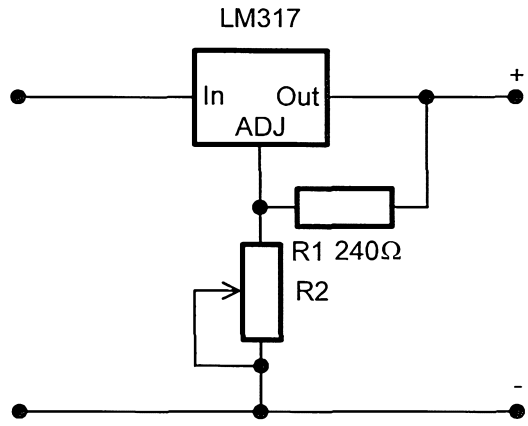


Figure 10 *The LM317 wired for a variable output voltage.*

Practise finding the output voltage of the LM317 circuit by attempting the following questions.

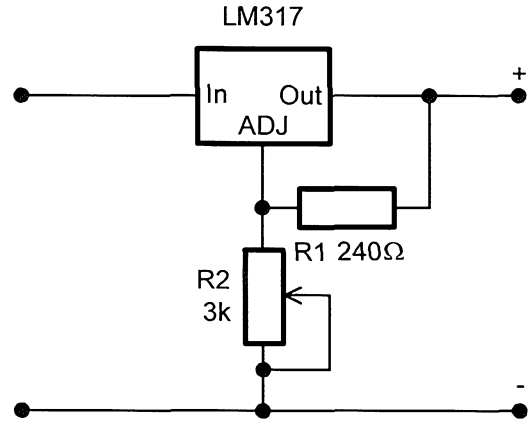


Figure 11

1. What is the minimum output voltage of the circuit in Figure 11 above? **Tip:** A calculation is not needed to answer this question.

2. Calculate the maximum output voltage of the circuit.

Student notes

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Skill practice 8

Practise measuring the output voltage of loaded 3-terminal regulator power supply circuits using a DMM

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- 15V AC power supply
- prototyping panel
- decade box
- two DMMs
- W04 bridge rectifier
- 7815 3-terminal regulator
- 100Ω 1W resistor
- 1.5kΩ resistor
- 1000µF 63V electrolytic capacitor
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the breadboard.

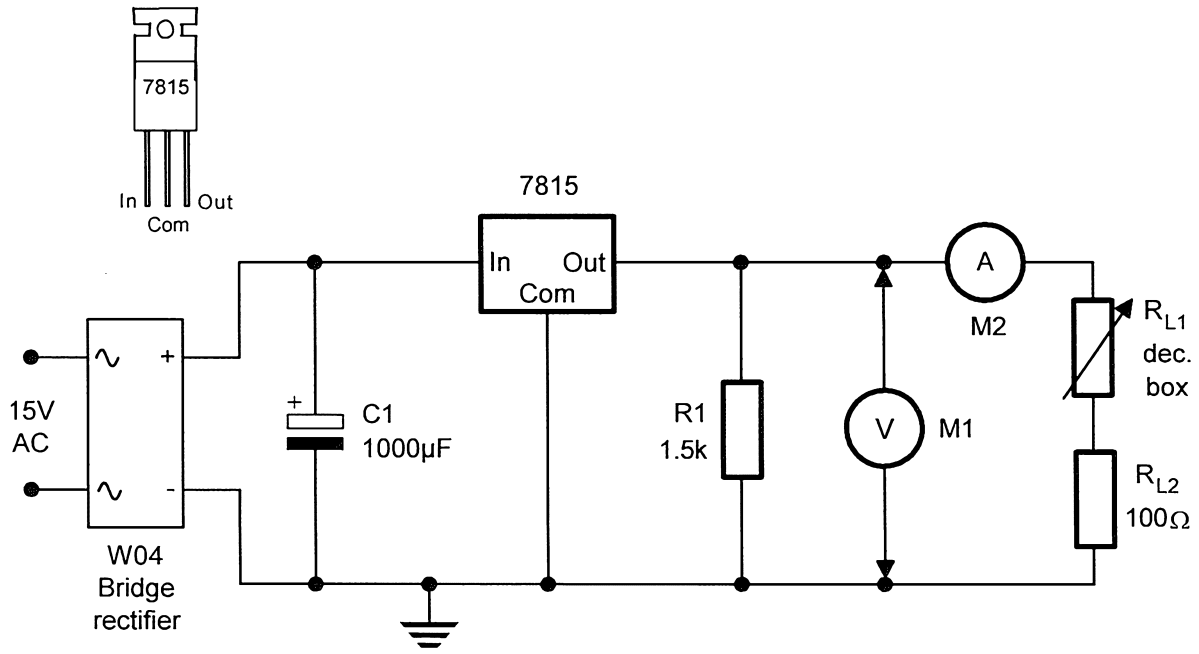


Figure 1

4. Read the brief circuit description below before proceeding, especially the note related to *R1*.

Circuit description
The bridge rectifier and filter capacitor (*C1*) form the unregulated power supply. The 7815 is the series voltage regulator. The load resistance is being provided by the series combination of R_{L1} and R_{L2}. M1 measures the effective DC output voltage from the power supply and M2 measures the load current.

Why has *R1* been added to the circuit?
Many 3-terminal regulator ICs are not designed to operate without a load. This isn't normally a problem because, in most cases, regulator ICs are operated with their load permanently connected.

However, to determine this regulator's load regulation performance, its necessary for you to disconnect the load to measure its no-load output voltage (V_{NL}). So, *R1* has been added to the circuit to draw the minimum current through the regulator that it needs to provide a regulated output.

5. Set the decade box's resistance for 2.4kΩ then turn on the AC power supply.

   Self check: If your circuit is working correctly, you should measure an output voltage of almost exactly 15V (on M1) and a load current of about 6mA (on M2). If you don't measure these values turn off the AC power supply immediately and check your wiring.

6. Disconnect the load from the circuit by disconnecting one of the wires to the decade box.

7. Measure the regulated DC output voltage. Record your measurement in the first row of Table 1 (below).

8. Reconnect the load.

9. Adjust the decade box's resistance until the load current is 10mA.

10. Measure and record the output voltage.

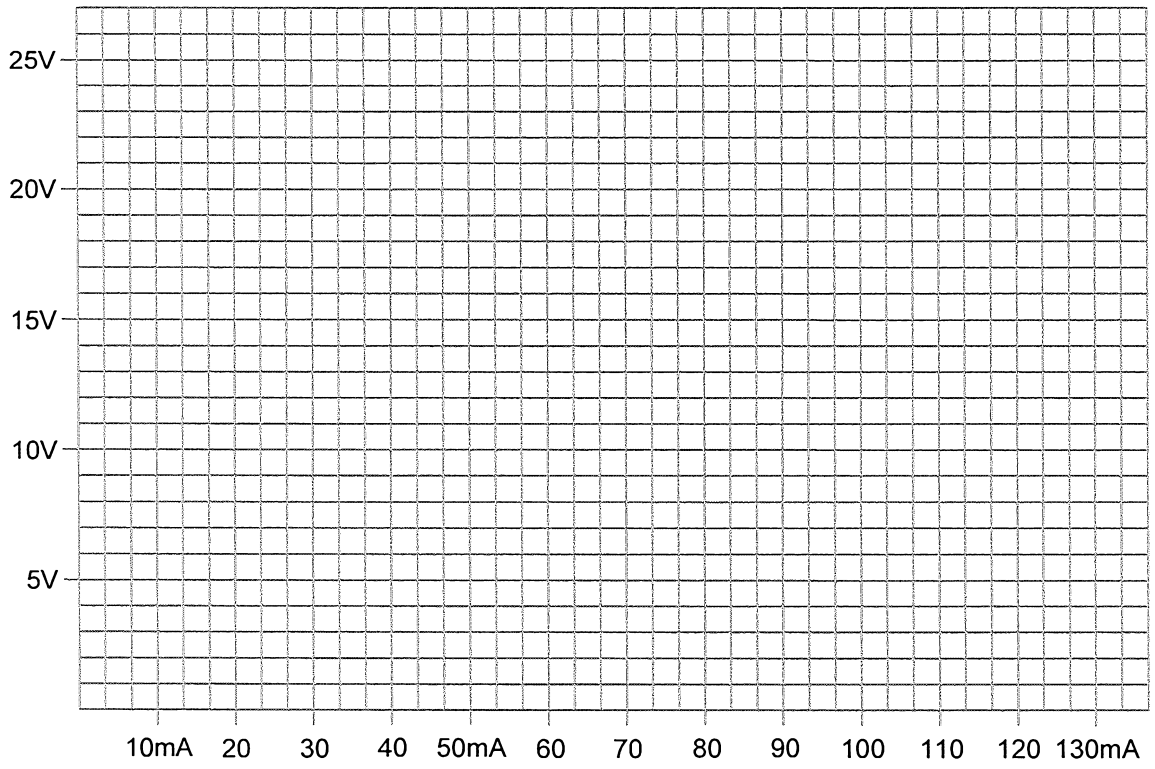
11. Repeat steps 9 and 10 for all the values of load current listed in Table 1.

12. Once the table is full, turn off the circuit.

Table 1

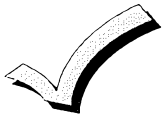
Load current	$Vout_{(DC\ regulated)}$	Load current	$Vout_{(DC\ regulated)}$
0mA		70mA	
10mA		80mA	
20mA		90mA	
30mA		100mA	
40mA		110mA	
50mA		120mA	
60 mA		130mA	

13. Draw a graph of load current versus load voltage on the graph below.



Question 1

Compare this graph with the graphed results for the same test conducted for Skill Practise 6 (see page 6-15) and Skill Practise 7 (see page 7-21). Explain why this graph is better.



The teacher needs to check your work at this point...

14. Calculate the circuit's load regulation percentage for the 40mA load current using the equation: $Load\ regulation = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100$. Record this figure in Table 2 below.

    Note: $V_{no-load}$ is the circuit's output voltage when the load current is zero. $V_{full-load}$ is the output voltage at 40mA.

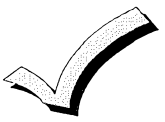
15. Repeat Step 14 for the other load currents listed in the table.

Table 2

Load current	Load regulation %
40mA	
60mA	
80mA	
100mA	

Question 3
Compare the figures in Table 2 with the same figures for the zener diode shunt regulator in Skill Practise 7 (see page 7-22). How does the 3-terminal regulator compare in terms of regulation? Explain your answer.

Question 4
Apart from providing much better regulation, what other advantage does the 15V 3-terminal regulator have over the 15V zener diode shunt regulator? [Tip: Compare your results in Table 1 of this practical with your results in Table 1 on page 7-21.]



The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. Draw the schematic symbol for a 3-terminal regulator and label the leads.

2. What is the output voltage of a 7805 3-terminal regulator?

   ☐ +7V
   ☐ -7V
   ☐ +5V
   ☐ -5V

3. What is the output voltage of a 7924 3-terminal regulator?

   ☐ +7V
   ☐ -7V
   ☐ +24V
   ☐ -24V

4. What is the minimum voltage allowed on the input of a 7805 3-terminal regulator for normal operation?

   ☐ 5V
   ☐ 7V
   ☐ 9V
   ☐ 12V

Questions 5 to 9 refer to the circuit in Figure 1

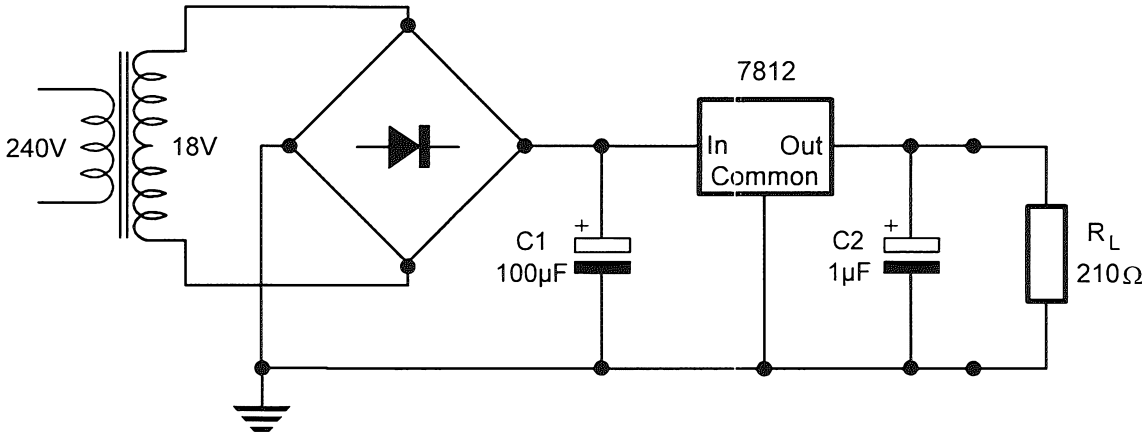


Figure 1

5. What is the potential difference across the load (V_{RL})?

6. What is the power dissipated by the load (P_{RL})?

7. What is the voltage across the filter capacitor (V_{Cl})?

8. What is the power dissipated by the 3-terminal regulator (P_{Reg})?

9. What modification can be made to the circuit to reduce the power dissipated by the 3-terminal regulator for the same value of load resistance?

Questions 10 and 11 refer to the circuit in Figure 2 below

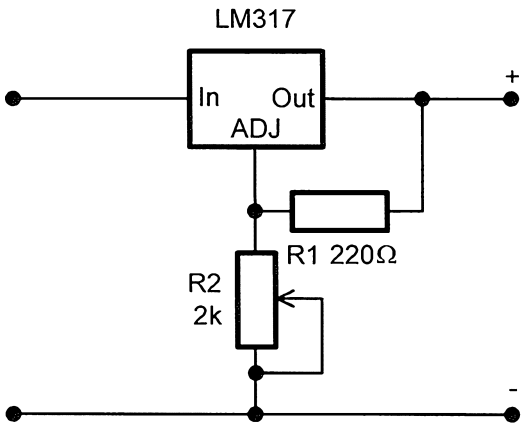


Figure 2

10. What is the circuit's minimum output voltage?

11. Calculate the circuit's maximum output voltage.

12. What's the typical dropout voltage of 3-terminal regulators?

13. What does the dropout voltage specification tell us about the normal operational requirements of 3-terminal regulators?

Appendix

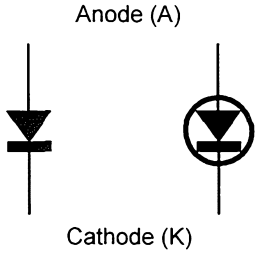
Section summaries

The theory notes in each Section of this workbook are designed to help you learn about the basic principles of linear power supplies. But when you think about it, there's a difference between learning and remembering. These section summaries are designed to help you remember the theory.

Section 1

Objectives and Summary

1. Draw the schematic symbol for a diode



2. Name and identify the terminals of a diode

   See above.

3. Name the semiconductor materials commonly used for diodes

   Silicon (Si) and germanium (Ge)

4. Describe the operation of a diode over a range of anode-cathode voltages

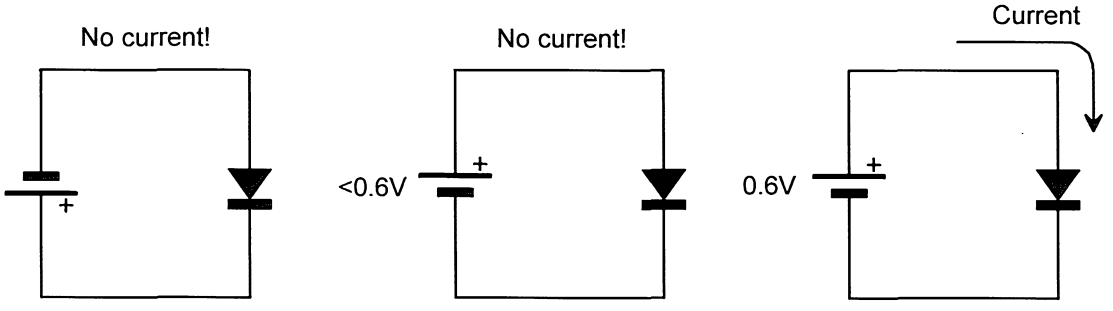


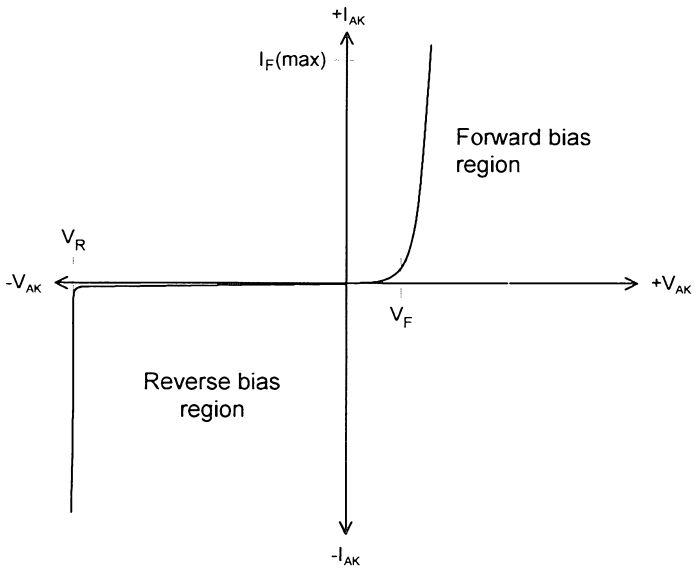
Figure A **Figure B** **Figure C**

5. Define the terms *reverse bias* and *forward bias*

   When a diode is *forward biased* it is turned on and conducting (conventional) current from anode to cathode. The diode in Figure C above is forward biased.

   When a diode is *reverse biased* it is turned off and conducting only a minute amount leakage current from cathode to anode. The diode in Figure A above is reverse biased.

6. Interpret the graph of anode-cathode voltage versus anode-cathode current of typical rectifier diodes



The summary for item 7 below will help you interpret this graph.

7. Define the terms *reverse breakdown voltage*, *reverse leakage current*, *forward voltage*, *forward current* and *maximum forward current*

Reverse breakdown voltage (V_R on the graph above) is the reverse bias voltage that, if exceeded, causes the diode to conduct in the reverse direction. Doing so usually damages the diode.

Reverse leakage current is the tiny amount of current that flows from cathode to anode when the diode is reverse biased. This current is in the order of nano amps and less.

Forward voltage (V_F on the graph above) is the critical voltage that turns the diode on. We say it's 0.6V but it's a range of possible voltages between about 0.5V and 0.7V.

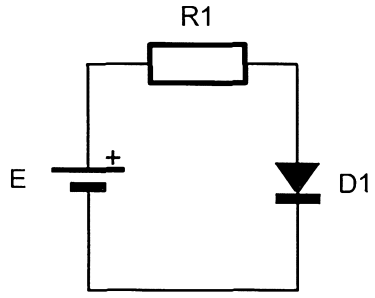
Forward current is the current that flows when the diode is forward biased (see Figure C on the previous page).

Maximum forward current ($I_{F(max)}$ on the graph above) is the maximum allowable forward current that the diode is capable of handling without damage.

8. Determine specified values of reverse breakdown voltage, reverse leakage current, forward voltage and maximum forward current of a diode from manufacturer's data

See data sheet given to you by the teacher in class. If you can't find these five key characteristics, see the teacher for assistance.

9. Calculate the current and potential differences around a series circuit consisting of a battery, diode and resistor in which the diode is reverse and forward biased

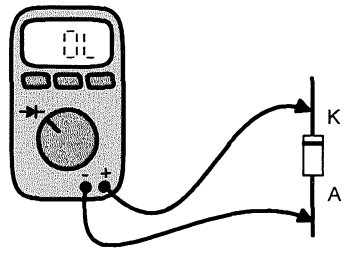


$$V_{R1} = E - 0.6V$$

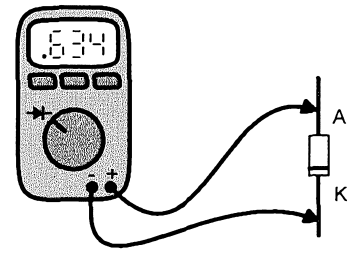
$$I = \frac{V_{R1}}{R1}$$

10. Conduct tests on diodes to identify the terminals and determine whether or not they are faulty

Typical readings for a working diode:

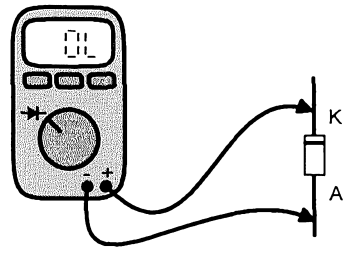


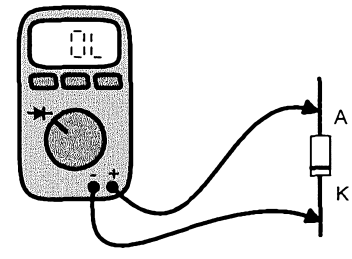
Diode reverse biased by the DMM



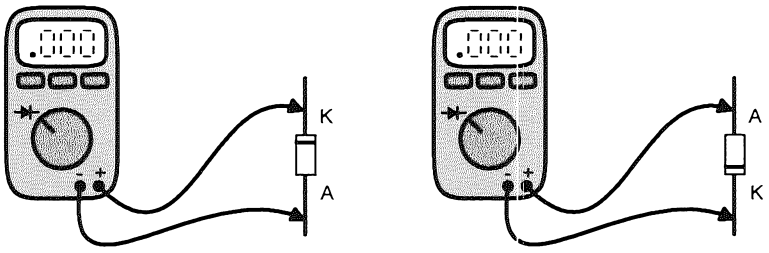
Diode forward biased by the DMM

Readings for an open-circuit diode:





Readings for a short-circuit diode:



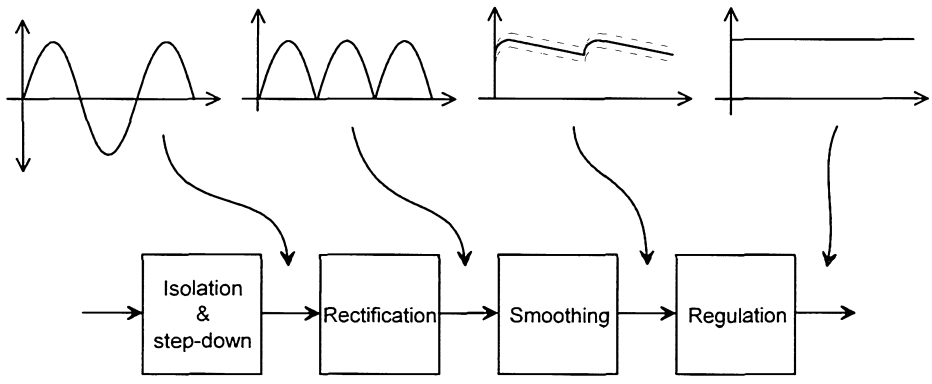
Section 2

Objectives and Summary

1. Explain the need for a power supply in electronics equipment

   Mains is an AC power distribution system but all electronics equipment operates from a DC supply. So power supplies are used to convert AC-to-DC converters to allow electronics equipment to run off mains. They're often internal but can be external as a "power-pack".

2. Draw the generic functional block diagram of a power supply



3. Explain the purpose of each block in the generic block diagram of a power supply

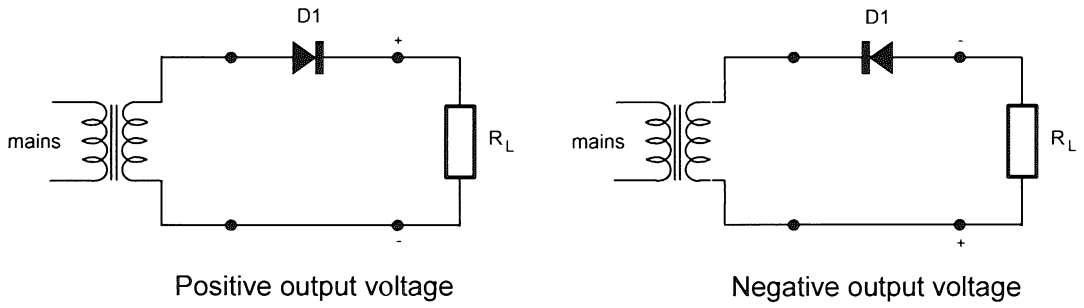
   Isolation and step-down: For safety reasons, this block isolates the power supply from any direct electrical contact with mains. It also decreases the relatively large mains voltages 340V peak (240V RMS) to a smaller AC voltage. See above.

   Rectification: This block converts the AC output of the first block into "pulsating DC". The pulsating DC is either half-wave rectified or full-wave rectified like that shown above.

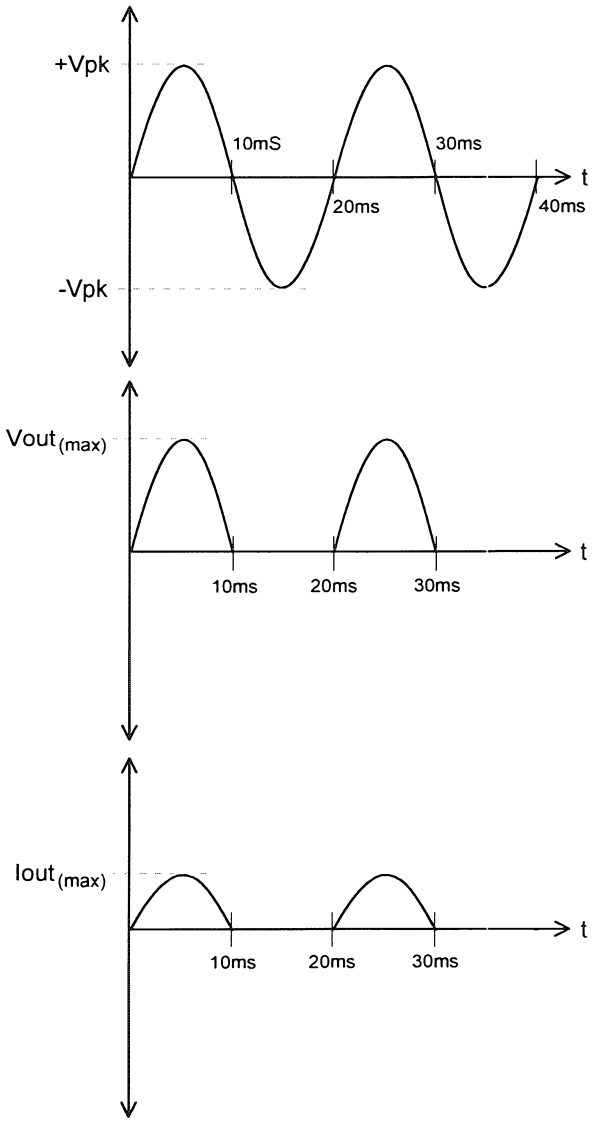
   Smoothing: This block converts the pulsating DC to a relatively smooth DC. However, it may still contain some AC (called "ripple") and can still vary up and down a little bit due to factors mentioned next.

   Regulation: This block almost totally removes the ripple and locks the DC output voltage at a set level so that it doesn't change due to changes in mains or changes in the load.

4. Draw the circuit of a half-wave rectifier to produce a positive or negative output voltage



5. Draw the potential difference and current waveforms for the **load** of a half-wave rectifier



6. State the frequency of the potential difference and current waveforms for the load of a half-wave rectifier

   50Hz

7. Calculate the maximum values of potential difference and current for the load of a half-wave rectifier given the transformer's primary voltage and turns ratio

   Use the review questions to practise this. The equations are:

   $Vs = \frac{V_P}{N}$

   $Vout_{(max)} = Vs_{(pk)} - 0.6V$

   $Iout_{(max)} = \frac{Vout_{(max)}}{R_L}$

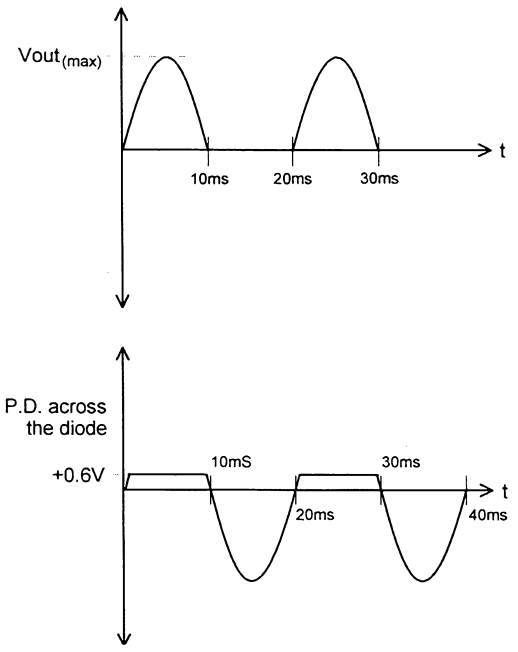
8. Calculate the average potential difference and current for the load of a half-wave rectifier given maximum values for each

   Use the review questions to practise this. The equations are:

   $Vout_{(av)} = Vout_{(max)} \times 0.318$

   $Iout_{(av)} = Iout_{(max)} \times 0.318$ or $Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$

9. Draw the waveform of the potential difference across the diode in a half-wave rectifier



10. Define the term *peak inverse voltage*

    This is the maximum reverse bias voltage that the rectifier diode(s) experiences in the circuit.

11. Calculate the peak inverse voltage of a half-wave rectifier circuit given the transformer's primary voltage and turns ratio

    $PIV = -Vs_{(pk)}$ (Where V_S is the mains transformer's secondary voltage)

12. Choose diodes with suitable specifications for the reverse breakdown voltage and forward current for half-wave rectifier circuits

    Class activity.

13. State an advantage and a disadvantage of the half-wave rectifier

    Advantages: Simplicity of design, fewer components, centre-tapped transformer not needed.

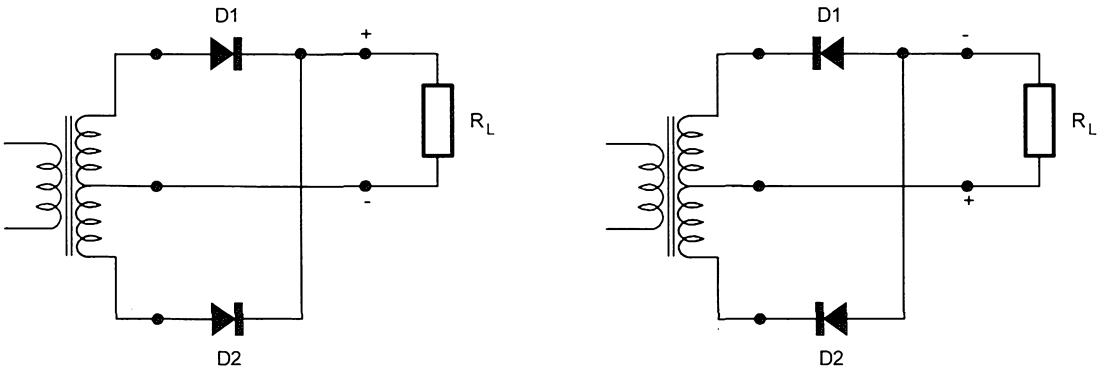
    Disadvantages: Need a bigger smoothing capacitor for a given level of ripple compared to the full-wave rectifiers

Section 3

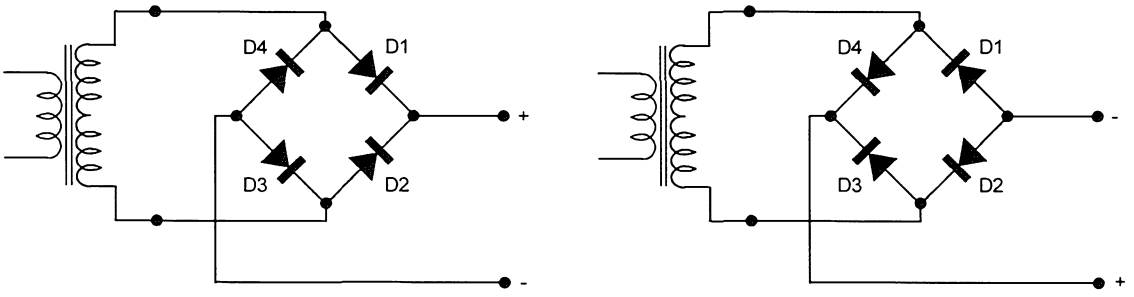
Objectives and Summary

1. Draw the circuit of a centre-tapped transformer full-wave rectifier and a bridge rectifier to produce a positive or negative output voltage

   Centre-tapped transformer full-wave rectifier

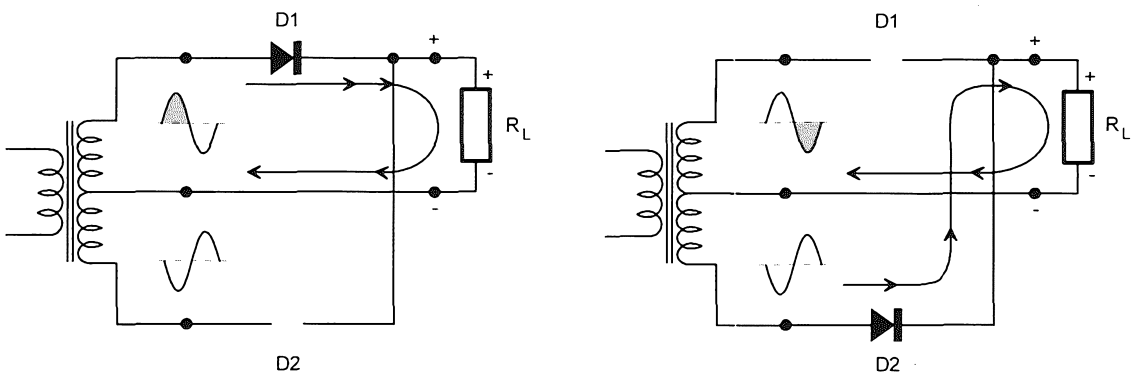


   Bridge rectifier

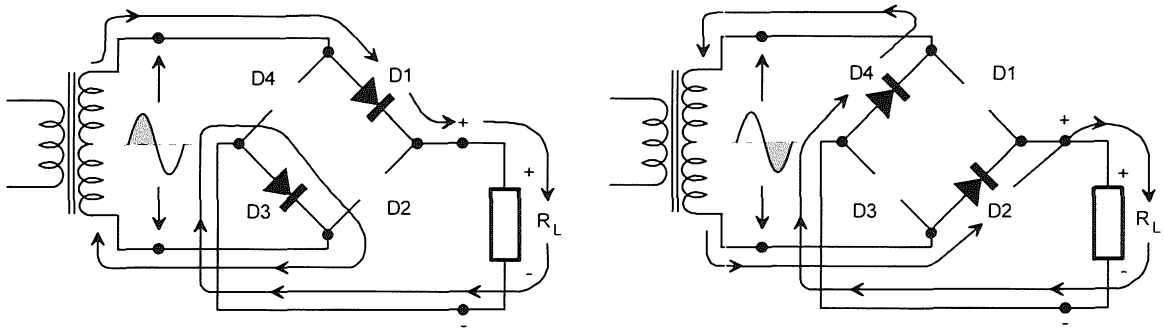


2. Show the current paths during each half cycle of the transformer's secondary voltage through the circuit of the two full-wave rectifier circuits

Centre-tapped...

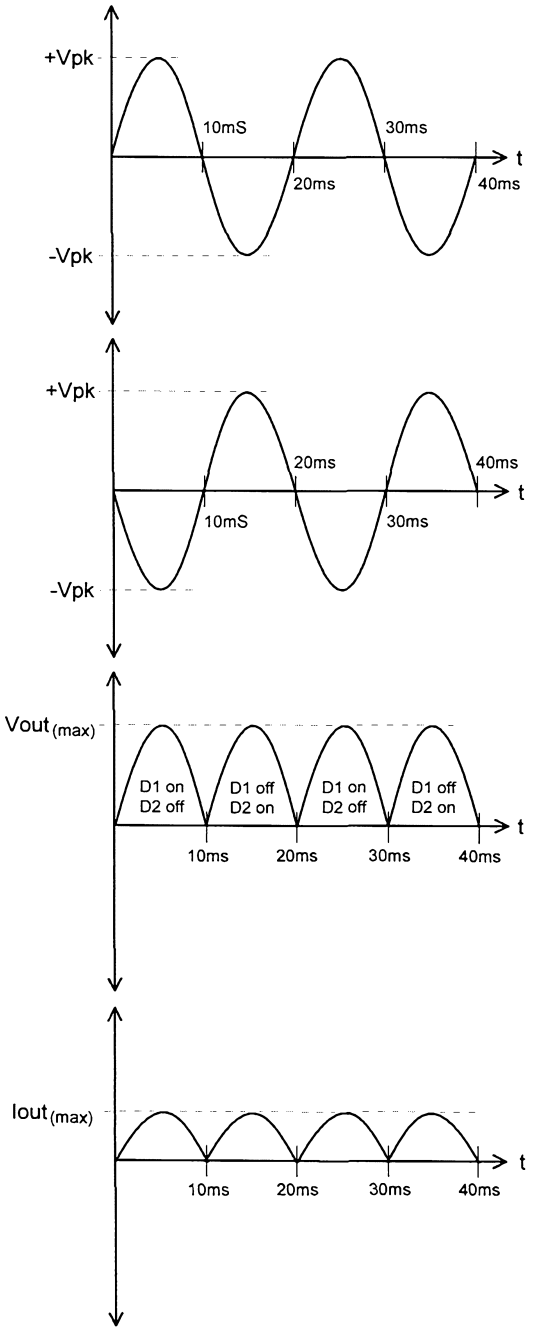


Bridge

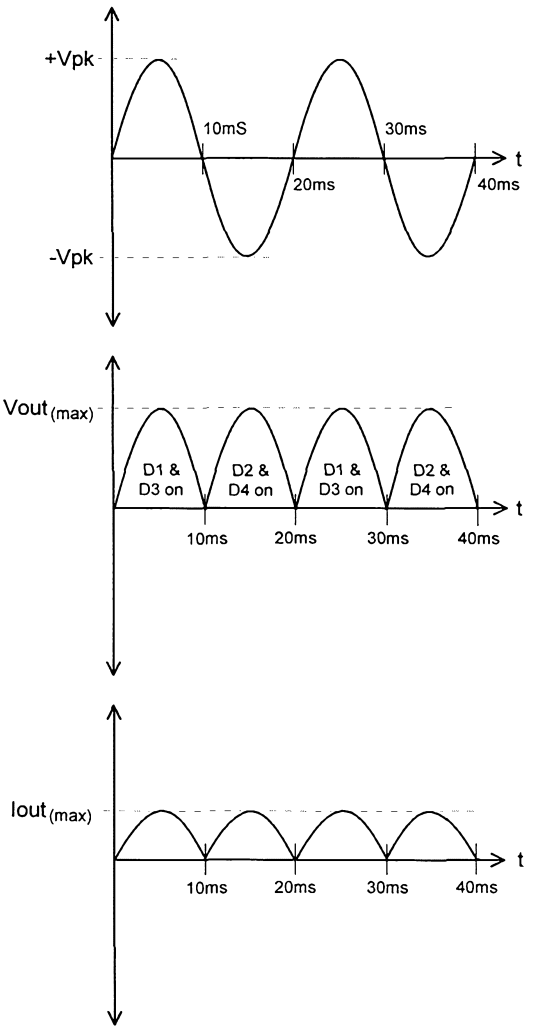


3. Draw the potential difference and current waveforms for the load of the two full-wave rectifier circuits

Centre-tapped...



Bridge



4. State the frequency of the potential difference and current waveforms for the load of the two full-wave rectifier circuits

   Both: 100Hz

5. Calculate the maximum values of potential difference and current for the load of the two full-wave rectifier circuits given the transformer's primary voltage and turns ratio

   Both: $Vs = \frac{V_P}{N}$

   Centre-tapped: $Vout_{(\max)} = Vs_{(pk)} - 0.6V$ Bridge: $Vout_{(\max)} = Vs_{(pk)} - 1.2V$

   Both: $Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$

6. Calculate the average potential difference and current for the load of the two full-wave rectifier circuits given maximum values for each

   Both: $Vout_{(av)} = Vout_{(\max)} \times 0.636$

   Both: $Iout_{(av)} = Iout_{(\max)} \times 0.636$ or $Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$

7. Draw the waveform of the potential difference across the diodes in the two full-wave rectifier circuits

   Not given in the workbook and so you wouldn't be asked to draw this in the test.

8. Calculate the peak inverse voltage of the two full-wave rectifier circuits given the transformers primary voltage and turns ratio

   Centre-tapped: $PIV = 2 \times Vs_{(pk)}$

   Bridge: $PIV = Vs_{(pk)}$

9. Choose diodes with suitable specifications for the reverse breakdown voltage and forward current for the two full-wave rectifier circuits given the load resistance

   Class activity.

10. State an advantage and a disadvantage of the two full-wave rectifier circuits

Advantages:

Both: Smaller smoothing cap required compared to half-wave rectification.

Centre-tapped: Fewer diodes needed compared to the bridge rectifier.

Bridge: No centre-tapped transformer required and PIV experienced by diodes is half that for the diodes in the centre-tapped circuit.

Disadvantages:

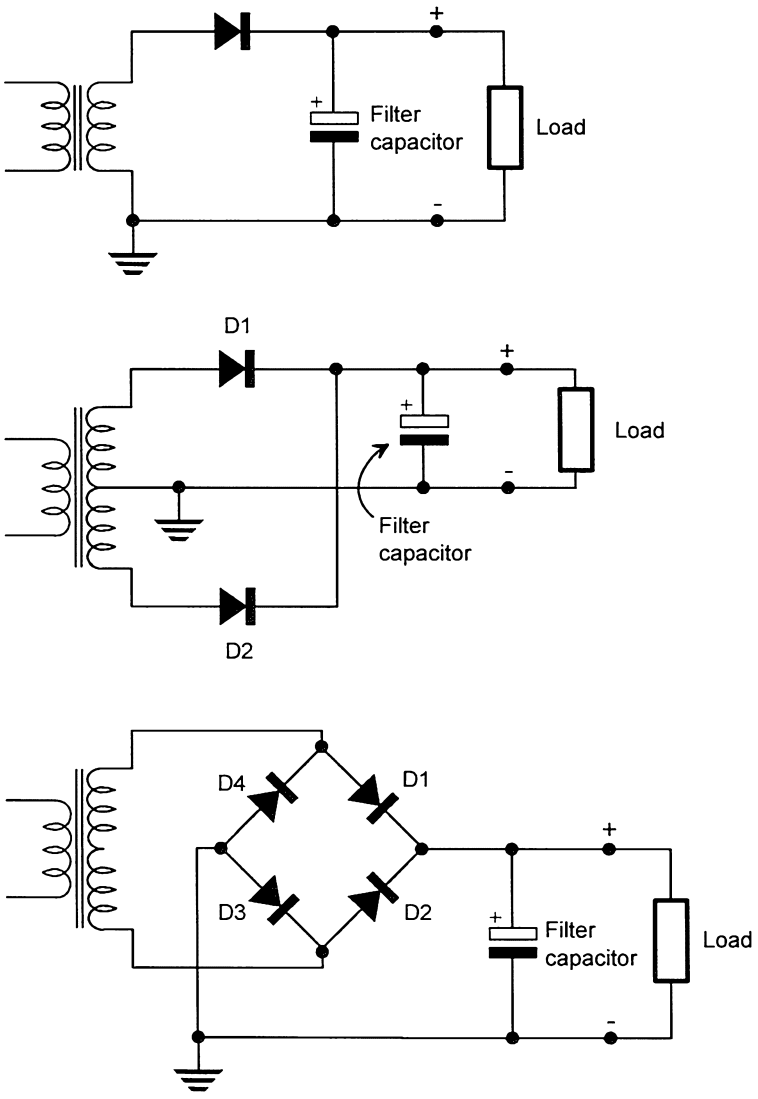
Centre-tapped: More expensive transformer required and double the PIV experienced by the diodes compared to the diodes in a bridge circuit.

Bridge: Four diodes needed instead of two (centre-tapped) or only one (half-wave).

Section 4

Objectives and Summary

1. Show where a *filter capacitor* is connected in the circuit of a half-wave and full-wave rectifier power supply



2. State the type of capacitor usually used for a filter capacitor

   Electrolytic (Aluminium oxide type).

3. Show the correct polarity for connecting a filter capacitor

   See the schematic diagrams on the previous page.

4. State the reason for a filter capacitor

   To smooth the pulsating DC on the rectifiers' output.

5. Explain how a filter capacitor smooths the pulsating DC of a rectifier output

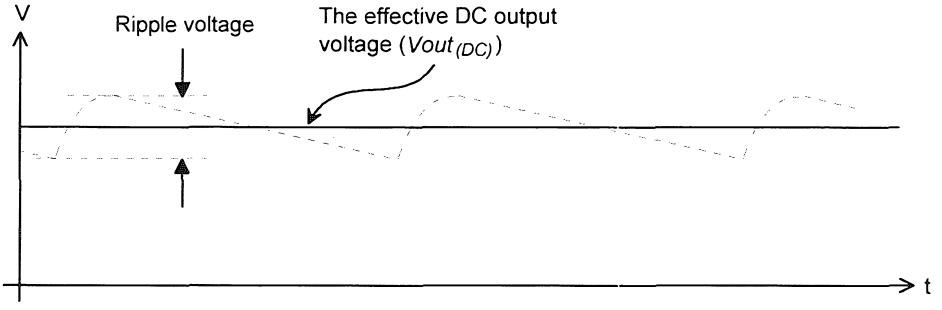
   The filter capacitor discharges via the load during the time that rectifiers' output falls below $Vout_{(max)}$. So, from the perspective of the load, there is no fall in voltage (ideally).

6. Define the terms *ripple voltage*, *ripple frequency* and *effective DC voltage*

   Ripple voltage: The AC voltage superimposed on the power supply's DC output voltage caused by the fall in potential difference across the filter capacitor as it discharges into the load (see diagram below).

   Ripple frequency: The frequency of the ripple voltage.

   Effective DC voltage: This is the DC voltage seen by the load for a power supply that has a ripple voltage on its output. The effective DC sits in between the ripple voltage's peaks (see diagram below).



7. State the ideal effective DC and ripple voltages for a filtered rectifier

   Ideal ripple voltage = 0V

   Ideal DC output voltage = $Vout_{(max)}$ (See notes from previous lessons for an explanation of what $Vout_{(max)}$ is.)

8. Calculate the effective DC voltage of a filtered rectifier given the maximum output voltage and the amplitude of the ripple voltage

   Use the review questions to practise this. The equation is:

   $$Vout_{(DC)} = Vout_{(\max)} - \left(\frac{Vout_{(ripple)(p-p)}}{2}\right)$$

9. State the ripple frequency of half-wave and full-wave rectifiers

   Half-wave rectifier: 50Hz

   Both full-wave rectifiers: 100Hz

10. Calculate the *ripple factor* given the effective DC and ripple voltages

    Use the review questions to practise this. The equation is:

    $$Ripple\ factor = \frac{Vout_{(ripple)(RMS)}}{Vout_{(DC)}} \times 100$$

11. State the ideal ripple factor for a filtered rectifier

    0%

12. List the factors that affect the effective DC and ripple voltages

    a) The type of rectifier used (full-wave is better than half-wave)
    b) The size of the filter capacitor (bigger is better)
    c) The size of the load (again bigger is better but this is not really a controllable property)

Objectives from previous Sections affected by the introduction of a filter capacitor

From Section 2:

1. Calculate the peak inverse voltage of a half-wave rectifier circuit given the transformer's primary voltage and turns ratio

   This changes from $PIV = -Vs_{(pk)}$ to $PIV = 2 \times -Vpk$

Note: The issue of how the filter capacitor affects the PIV of diodes in rectifiers is summarised as in the table below.

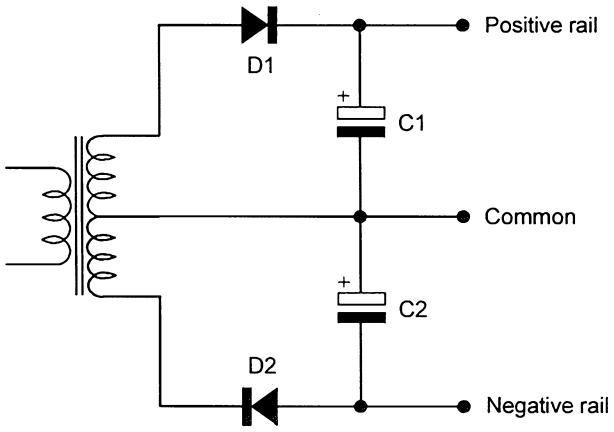
	Rectifier type		
	Half-wave	**Centre-tapped**	**Bridge**
No filter cap	$PIV = -Vs_{(pk)}$	$PIV = 2 \times Vs_{(pk)}$	$PIV = Vs_{(pk)}$
Filter cap	$PIV = 2 \times -Vpk$	Same as above	Same as above

Section 5

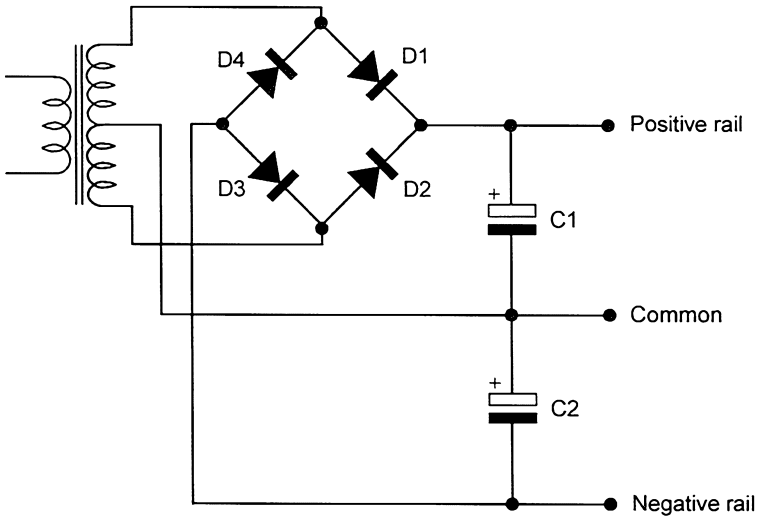
Objectives and Summary

1. Draw and explain the operation of various filtered rectifier circuits that simultaneously provide a positive and negative DC output voltage

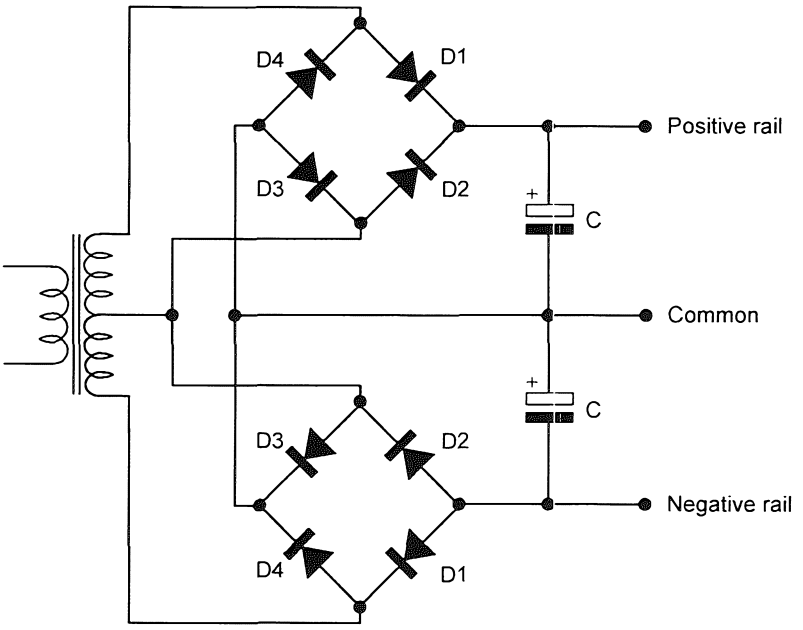
Half-wave rectified dual rail supply
(operation same as two single rail half-wave supplies)



Centre-tapped transformer dual rail supply
(operation same as two single rail tapped-transformer supplies)



Bridge rectifier dual rail supply
(operation same as two single rail bridge rectifier supplies)



2. List the faults that can occur with filtered rectifier circuits

Transformer

- Short-circuit primary winding
- Open-circuit primary winding
- Short-circuit secondary winding
- Open-circuit secondary winding
- Short-circuit between primary and secondary winding

Diodes

- Short-circuit anode-cathode
- Open-circuit anode-cathode

Filter capacitor

- Open-circuit
- Leaky

3. Describe the effect of each of these faults on the performance of filtered rectifier circuits

Note: It's probably better that you don't try to memorise these. Derive the fault symptoms by thinking about how that fault would change the performance of the component and then use this to think about how this would change the performance of the circuit. This is what good technicians can do. As an exercise, do this now and compare your thoughts with the theory notes.

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Section 6

Objectives and Summary

1. Explain the need for a *regulator* in DC power supplies

   DC power supplies need a regulator because their DC output voltage can vary due to either: a) variations in load resistance; and/or b) variations in mains (or "line") voltage.

2. Explain the purpose of a regulator in DC power supplies

   Regulators work to keep the power supply's DC output voltage constant.

3. Define the terms *load regulation* and *line regulation*

   Load regulation: The ability of a regulator to keep the power supply's DC output voltage constant for changes in load resistance.

   Line regulation: The ability of a regulator to keep the power supply's DC output voltage constant for changes in the mains voltage.

4. Name the two regulator connections

   Shunt and series

5. Explain the principle of operation of shunt and series regulation

   Shunt regulation keeps the output voltage constant by keeping the potential difference across the regulating device (which is connected in parallel with the load) constant despite changes in line and/or load.

   Series regulation keeps the output voltage constant by actively varying the potential difference across the regulating device (which is connected in series with the load) to compensate for changes in line and/or load.

6. Calculate the (load) regulation percentage, the no-load output voltage or the full-load output voltage of a regulated power supply given two of the three quantities

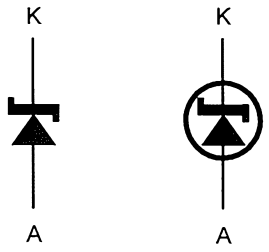
   Use the review questions to practise this. The equation is:

$$Load\ regulation = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100$$

Section 7

Objectives and Summary

1. Draw the schematic symbol for a zener diode

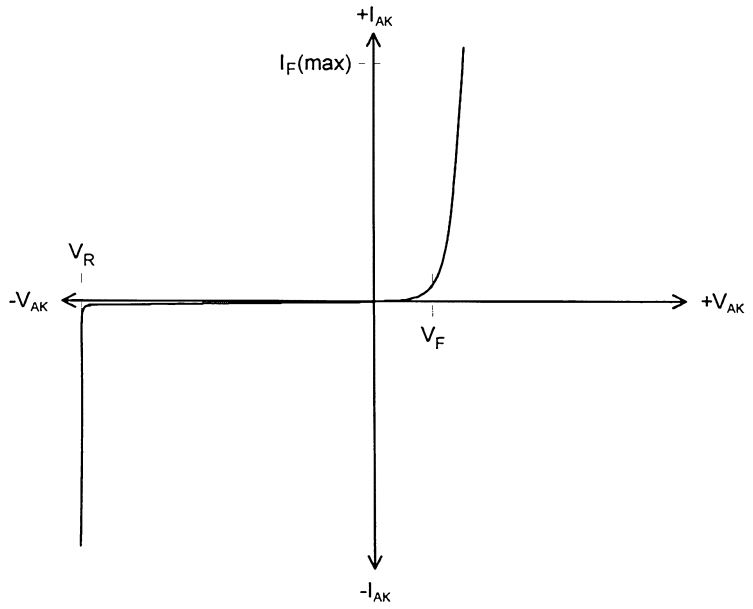


2. Name and identify the terminals of a zener diode

   See above where "A" denotes anode and "K" denotes cathode.

3. Interpret the graph of the potential difference versus current characteristic of typical zener diodes

   The diode's V_{AK}-I_{AK} characteristic is shown below.



4. Describe the similarities and differences between zener diodes and rectifier diodes in terms of their reverse breakdown voltage, reverse leakage current, forward voltage and maximum forward current

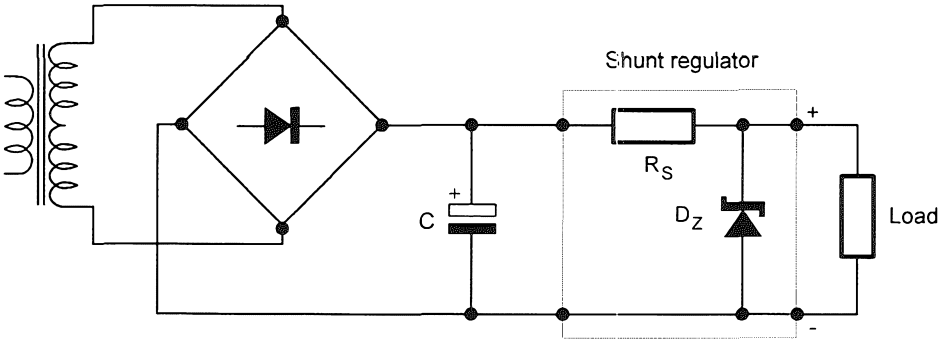
   The graph on the previous page is essentially identical to that of a rectifier diode and the devices are almost identical in terms of performance. The differences occur in the values for the diodes' key specifications. In particular, the value of V_R for rectifier diodes should be as high as possible whereas the V_R for zener diodes is usually much smaller and is a specific amount (see Item 5 below).

5. List typical values for the reverse breakdown voltage (V_R) of commercially available zener diodes

   3.3V, 3.9V, 4.7V, 5.1V, 5.6V, 6.2V, 6.8V, 7.5V, 8.2V, 9.1V, 10V, 12V, 15V, 16V, 18V, 20V, 24V, 30V and 33V.

6. Draw the schematic diagram of a zener diode shunt regulator circuit

   The shunt regulator is shown below as part of a complete linear power supply.



7. Explain the operation of a zener diode shunt regulator circuit

   a) The regulated DC output voltage of this circuit (and the voltage across the load) is set by the zener diode's rated zenering voltage (V_R).

   b) The zener regulates the output voltage by automatically adjusting its resistance so that, if the load current goes up, the zener diode current goes down and vice versa. This effectively prevents Kirchhoff's Voltage Law from determining the potential difference across the load.

8. Determine the output voltage of a zener diode shunt regulator circuit given the unregulated DC input voltage and the zener diode's reverse breakdown voltage

   $Vout_{(DC\ regulated)} = V_{DZ}$ where V_{DZ} is the diode's reverse breakdown voltage V_R

9. Calculate the current through, and the power dissipated by, the components in a zener diode shunt regulator given the unregulated DC input voltage and the zener diode's reverse breakdown voltage

   Use the review questions to practise this. The equations are:

   $V_{RS} = Vin_{(DC\ unregulated)} - Vout_{(DC\ regulated)}$

   $I_{RS} = \frac{V_{RS}}{R_S}$

   $I_{RL} = \frac{V_{RL}}{R_L}$

   $I_{DZ} = I_{RS} - I_{RL}$

   $P_{RS} = I_{RS} \times V_{RS}$ or $P_{RS} = \frac{V_{RS}^2}{R_S}$ or $P_{RS} = I_{RS}^2 \times R_S$

   $P_{DZ} = I_{DZ} \times V_{DZ}$

10. Conduct tests on zener diodes to identify the terminals and determine whether or not they are faulty

    See the summary for Section 1. The process is the same and will identify whether the zener diode is open-circuit or short-circuit. That said, this test will not identify the device's zenering voltage. However, if the device isn't open or short, it'll likely be working.

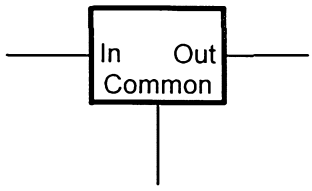
    To test the device's zenering voltage, put it in series (reverse biased) with a 1kΩ resistor and an EMF set to 5V above the device's rated zenering voltage. Then measure the potential difference across the zener. If it's about right (say ±20%) then that should be fine in most situations (though still not a guarantee!).

    If the device's zenering voltage is unknown and this needs to be found, connect it in series (reverse biased) with a 1kΩ resistor and an EMF set to 0V. Then steadily increase the EMF voltage until the potential difference across the zener diode is no-longer the same as the EMF.

Section 8

Objectives and Summary

1. Draw and label the schematic symbol of a 3-terminal regulator

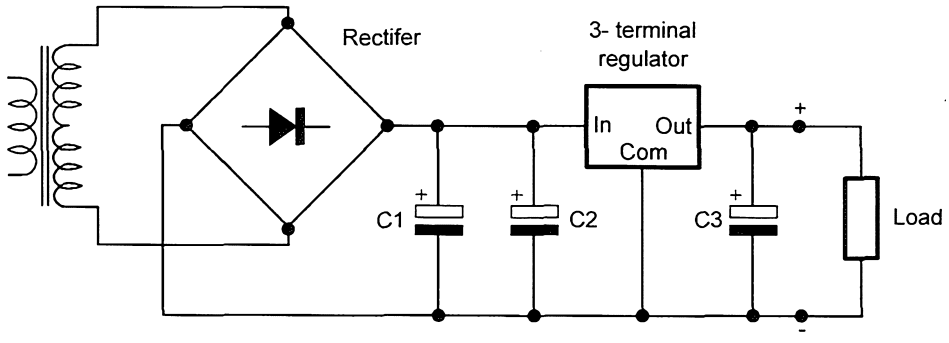


2. List the packages of common commercially available 3-terminal regulators

   TO-92, TO-220, TO-3 and TO-252 packages

3. Recognise series regulator circuits implemented using 3-terminal regulators

   The 3-terminal series regulator is shown below as part of a complete linear power supply.



4. Explain the purpose of the capacitors that are commonly connected across the input terminals and output terminals of 3-terminal regulators

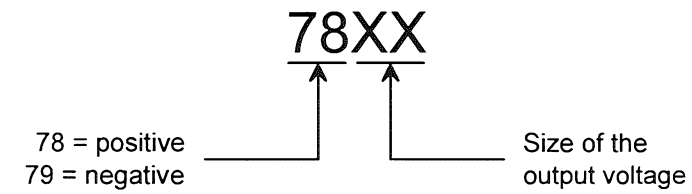
   Capacitor *C2* is typically 100nF and is used to shunt noise to common.

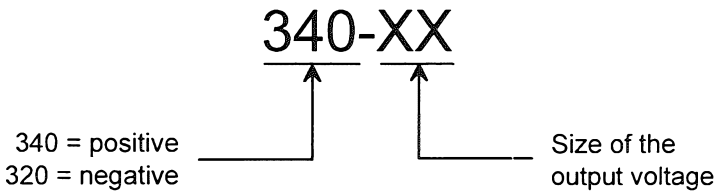
   Capacitor *C3* is sometimes added to help improve the circuit's stability (that is, to help prevent it from oscillating at a high frequency) by ensuring that the gain of the circuit is 1 (one) at high frequencies.

5. Define the term *dropout voltage*

   This minimum allowable difference between the input and output voltages of a 3-terminal regulator. Typically, it's 2V but this can vary from device to device.

6. Identify the DC output voltage of common commercially available 3-terminal regulators given a part number





7. Calculate the output voltage of a 3-terminal regulator circuit given the unregulated DC input voltage and the 3-terminal regulator's part number

   $Vout_{(DC\ regulated)}$ = *The regulator's rated output voltage*

8. Calculate the current through, and the power dissipated by, the components in a 3-terminal regulator given the unregulated DC input voltage and the 3-terminal regulator's part number

   Use the review questions to practise this. The equations are:

   $$I_{Reg} = I_{RL} = \frac{V_{RL}}{R_L}$$

   $$P_{Reg} = I_{Reg} \times (Vin_{(Reg)} - Vout_{(Reg)})$$

9. Predict the voltage on the output of the LM317 3-terminal regulator (for both fixed and variable outputs)

   Use the review questions to practise this. The equation is:

$$Vout = 1.25\left(\frac{R2}{R1} + 1\right) + 50\mu A \times R2$$

Answers to review questions

Section 1

1.

2. See above.
3. Silicon. (Note: Germanium is still used but not all that often these days.)
4. A layer of N-type and P-type semiconductor materials connected to each other.
5. P-type
6. reverse biased.
7. None.
8. 5μA is a typical figure.
9. Reverse leakage current.
10. neither forward or reverse biased.
11. forward biased.
12.

13. Reverse breakdown voltage
14. Conducting leakage current
15. Forward bias voltage
16. Conducting forward current
17. Maximum forward current

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Section 1 (continued)

18. (a) 800V
    (b) 5μA @ 800V
    (c) 1A
    (d) 1.1V @ 1A

19. 15V [Note: the diode is reverse biased so it acts like an open-circuit.]

20. 0V [Note: if no current flows in the circuit then there is no potential difference across the resistor.]

21. 0A

22. 0.6V

23. 14.4V

24. $I = \frac{V_R}{R}$

    $I = \frac{14.4V}{1k2\Omega}$

    $I = 12mA$

25. $P_R = I^2 \times R$ or $P_R = \frac{V_R^2}{R}$ or $P_R = V_R \times I_R$

    $P_R = 12mA^2 \times 1k2\Omega$ $P_R = \frac{14.4V^2}{1k2\Omega}$ $P_R = 14.4V \times 12mA$

    $P_R = 172.8mW$ $P_R = 172.8mW$ $P_R = 172.8mW$

26. $P_D = V_D \times I_D$

    $P_D = 0.6V \times 12mA$

    $P_D = 7.2mW$

27. 9V

28. 0V

29. 0A

Section 1 (continued)

30. 0.6V

31. 8.4V

32. 25.45mA

33. 213.8mW

34. Low resistance for test 1 and high resistance for test 2

35. The diode is open-circuit.

36. The diode is short-circuit.

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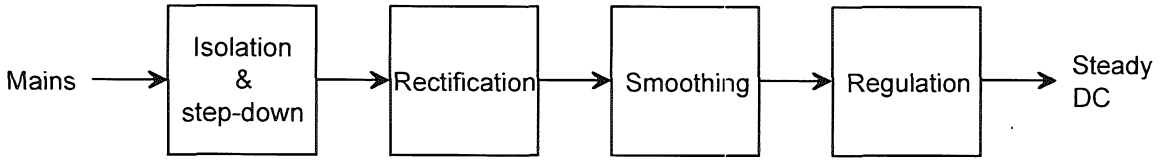
Section 2

1.



2. The rectification block

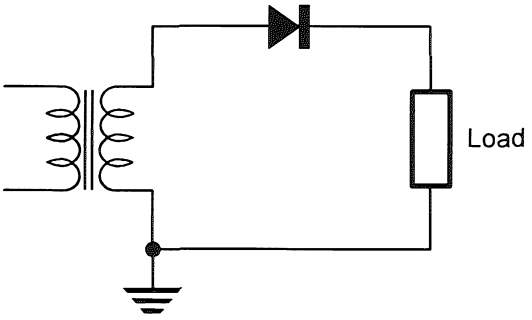
3. The regulation block

4. The smoothing block

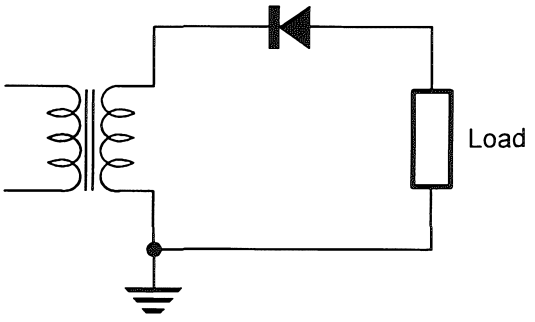
5. a) to step the mains voltage down to useable levels for electronics equipment

   b) to provide electrical isolation for the electronics equipment from the mains

6.



7.



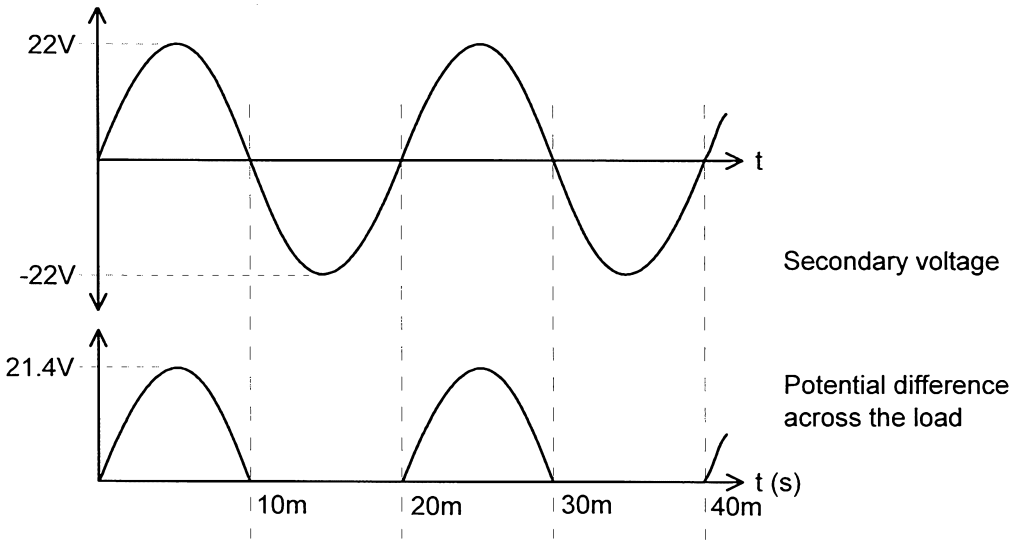
Section 2 (continued)

8. $Vout_{(\max)} = Vs_{(pk)} - 0.6V$

$Vout_{(\max)} = 22V - 0.6V$

$Vout_{(\max)} = 21.4V$

9.



10. 50Hz

11. $Vout_{(av)} = 0.318 \times Vout_{(\max)}$

$Vout_{(av)} = 0.318 \times 21.4V$

$Vout_{(av)} = 6.8V$

12. $Iout_{(\max)} = \frac{Vout_{(\max)}}{R_L}$

$Iout_{(\max)} = \frac{21.4V}{78\Omega}$

$Iout_{(\max)} = 274.3mA$

13. $Iout_{(av)} = \frac{Vout_{(av)}}{R_L}$

$Iout_{(av)} = \frac{6.8V}{78\Omega}$

$Iout_{(av)} = 87.18mA$

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Section 2 (continued)

14. the positive half-cycle of the secondary voltage.

15. $PIV = -V_P$

    $PIV = -22V$

16. At least twice the PIV (44V) or, better still, three times the PIV (66V)

17. the negative half-cycle of the secondary voltage.

18. The secondary voltage is 12V RMS. The peak secondary voltage is 16.97V.
    So, $Vout_{(max)} = 16.37V$

19. 5.2V

20. 109.1mA

21. 34.67mA

22. -16.97V

23. -38.29V

24. -12.17V

25. -683.8mA [Note: the negative sign can be left off this figure because it only indicates that current is travelling up the resistor instead of down it.]

26. 217.3mA

27. the negative half-cycle of the secondary voltage.

28. 39V

29. Advantage: The circuit is simple.

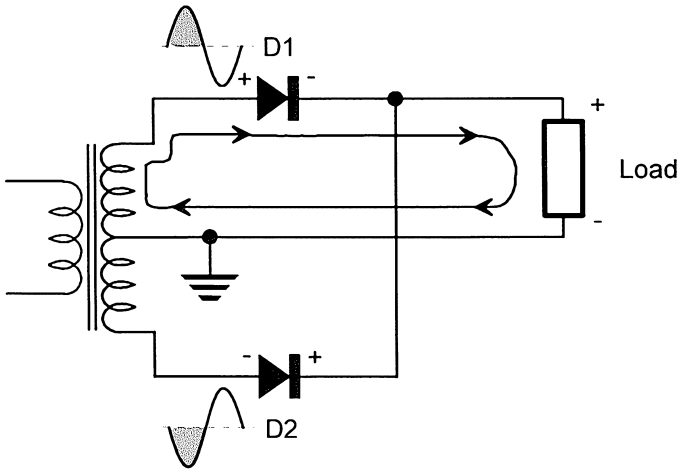
    Disadvantage: The big gap between the pulses of DC at the output of the half-wave rectifier requires smoothing circuitry that is physically much larger than the smoothing circuitry of the full-wave rectifiers.

Section 3

1. Centre-tapped transformer full-wave rectifier

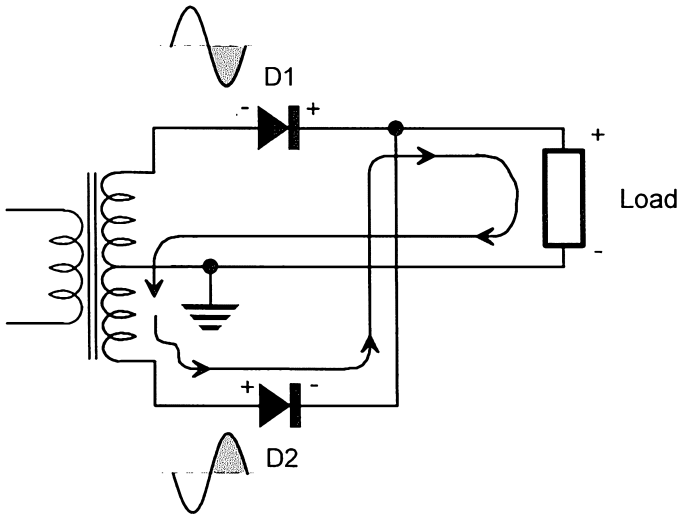
2. Positive voltage DC

3.



4. See the diagram above.

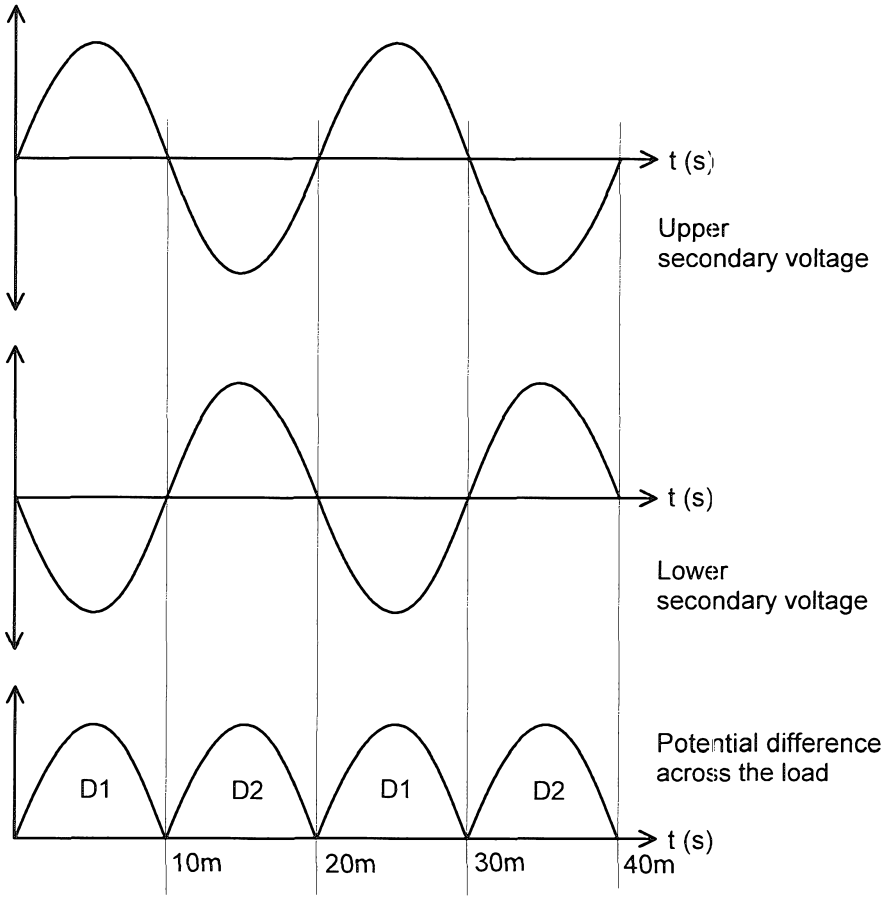
5.



6. See the diagram above.

Section 3 (continued)

7.



8. 100Hz

9. See the diagram above.

10. D1 could not conduct during the positive half-cycle of the secondary voltage and the waveshape across the load would look like a half-wave rectified signal.

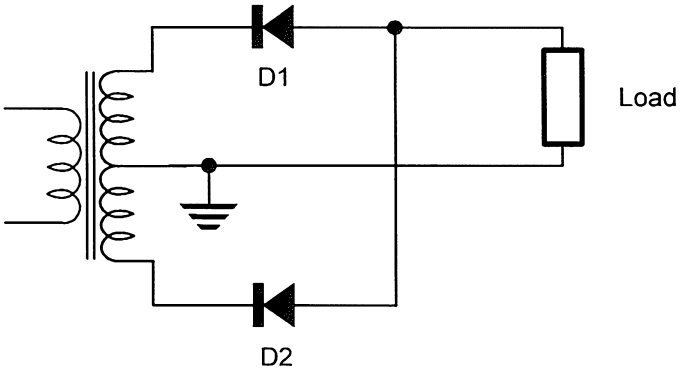
11. The average voltage would halve (to 0.318 of $Vout_{(max)}$).

12. With D2 short-circuit, the secondary windings of the transformer would be short-circuited during the positive half-cycle of the secondary voltage because D1 conducts during this time.

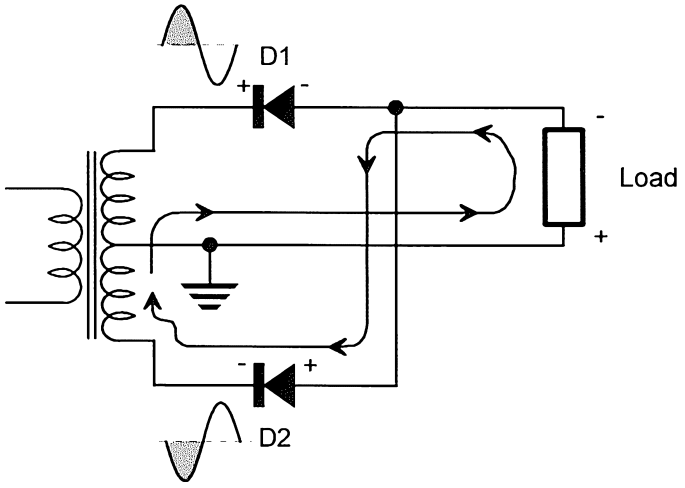
    [Note: This would cause a large secondary and primary current to flow. The fuse on the primary would probably blow but diode D1 may be damaged by the large secondary current.]

Section 3 (continued)

13.

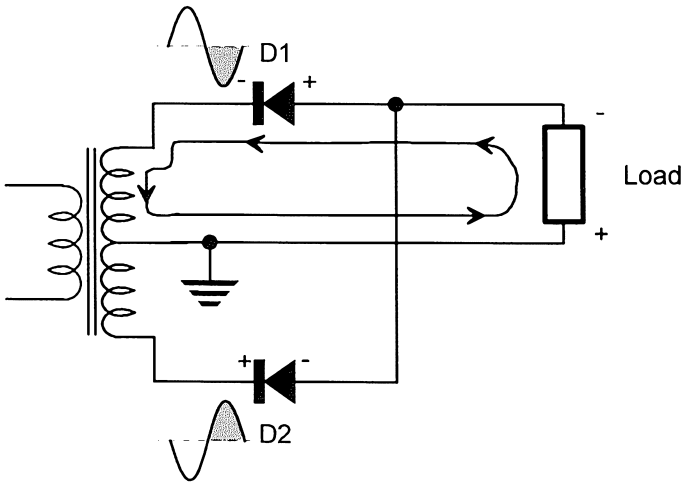


14.



15. See the diagram above.

16.



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Section 3 (continued)

17. See the diagram above.

18. $Vout_{(\max)} = V_P - 0.6V$

    $Vout_{(\max)} = 34V - 0.6V$

    $Vout_{(\max)} = 33.4V$

19. $Vout_{(av)} = 0.636 \times Vout_{(\max)}$

    $Vout_{(av)} = 0.636 \times 33.4V$

    $Vout_{(av)} = 21.24V$

20. 556.7mA

21. 354mA

22. $PIV = 2 \times V_P$

    $PIV = 2 \times 34V$

    $PIV = 68V$

23. At least 136V and preferably 204V

24. the negative half-cycle of the secondary voltage.

25. the positive half-cycle of the secondary voltage.

26. The smoothing circuit for the full-wave rectifier is smaller than the same circuit for the half-wave rectifier.

27. A centre-tapped transformer is necessary and these can be more expensive than a non-tapped transformer.

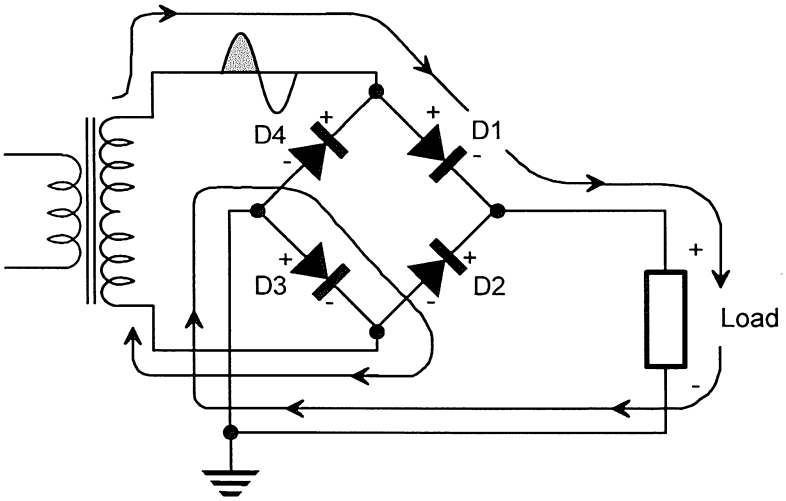
    [Note: It might be tempting to say that with more components (ie two diodes instead of one) the chances of the power supply developing a fault have doubled but probability doesn't work this way.]

28. Bridge rectifier

Section 3 (continued)

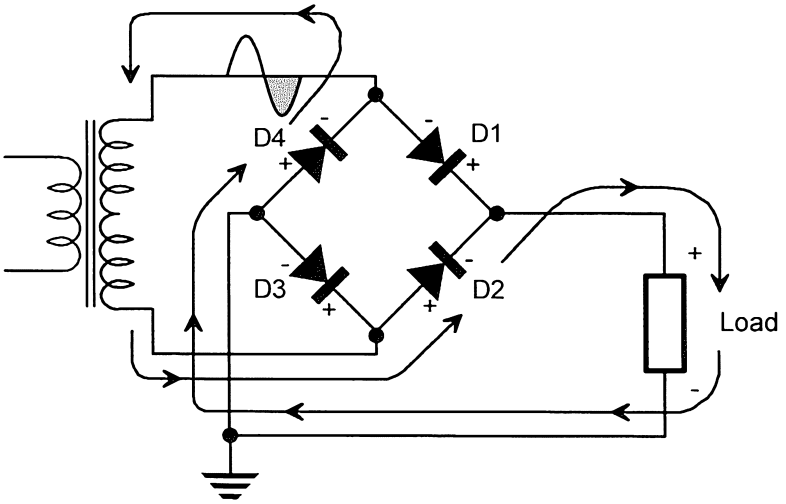
29. Positive voltage DC

30.



31. See the diagram above.

32.



33. See the diagram above.

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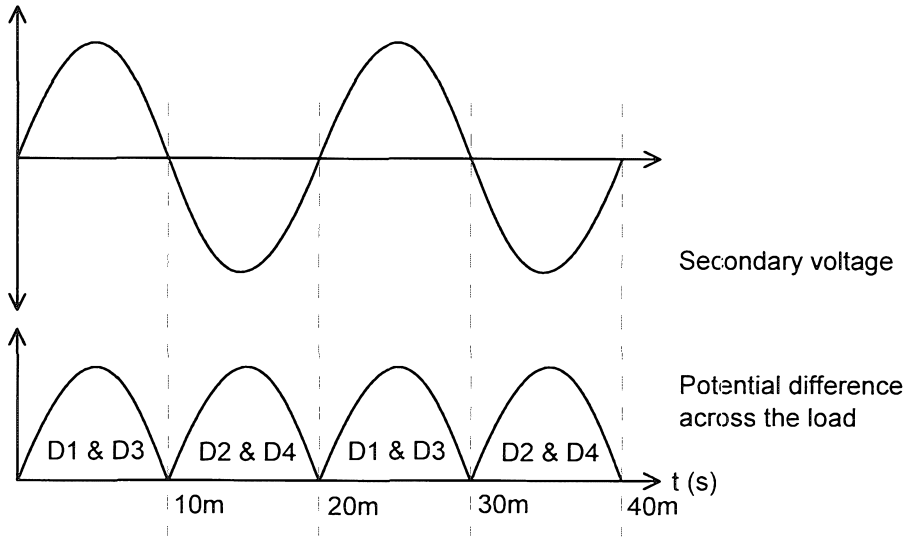
Section 3 (continued)

34.



35. See the diagram above.

36. D1 could not conduct during the positive half-cycle of the secondary voltage and the waveshape across the load would look like a half-wave rectified signal.

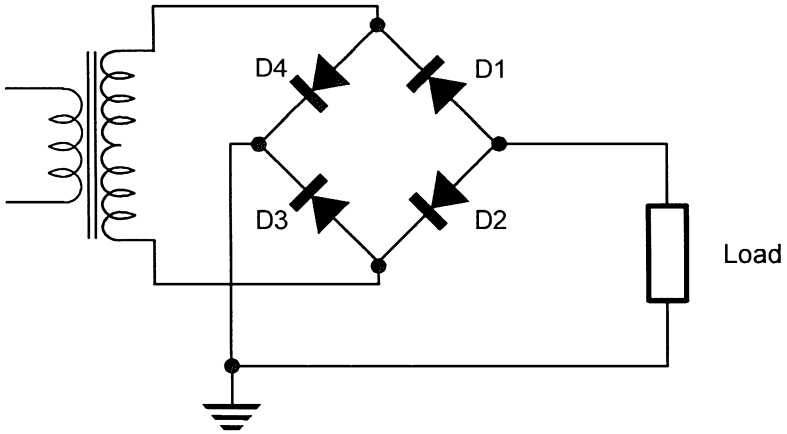
37. The average voltage would halve (to 0.318 of $Vout_{(max)}$).

38. With D2 short-circuit, the secondary windings of the transformer would be short-circuited during the positive half-cycle of the secondary voltage because D1 conducts during this time.

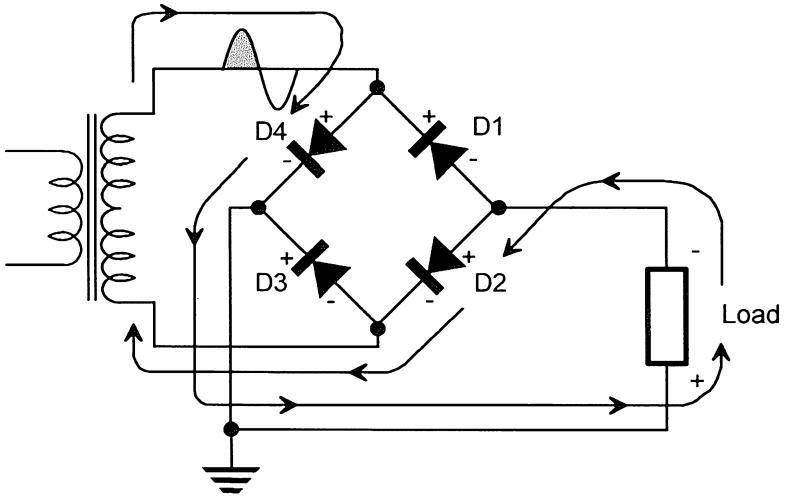
    [Note: This would cause a large secondary and primary current to flow. The fuse on the primary would probably blow but diode D1 may be damaged by the large secondary current.]

Section 3 (continued)

39.



40.



41. See the diagram above.

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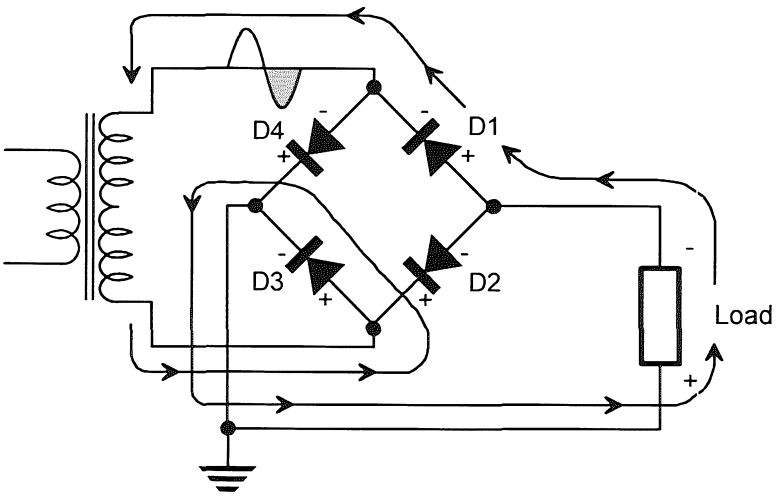
Section 3 (continued)

42.



43. See the diagram above.

44. $Vout_{(\max)} = V_P - 1.2V$

$Vout_{(\max)} = 85V - 1.2V$

$Vout_{(\max)} = 83.8V$

45. $Vout_{(av)} = 0.636 \times Vout_{(\max)}$

$Vout_{(av)} = 0.636 \times 83.8V$

$Vout_{(av)} = 53.3V$

46. 931.1mA

47. 592.2mA

48. $PIV = -V_P$

$PIV = -85V$

49. the negative half-cycle of the secondary voltage.

50. the positive half-cycle of the secondary voltage.

Section 3 (continued)

51. It is easier to smooth the DC.

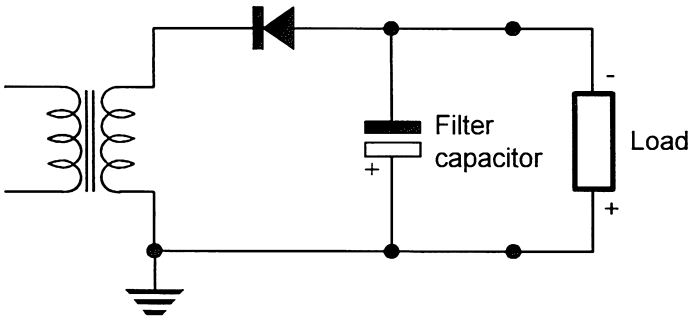
52. A non-tapped transformer can be used (which are cheaper than centre-tapped transformers because they're easier to make).

    Diodes with a smaller reverse breakdown voltage can be used (for the same output voltage) because the diodes in a bridge rectifier experience half the PIV.

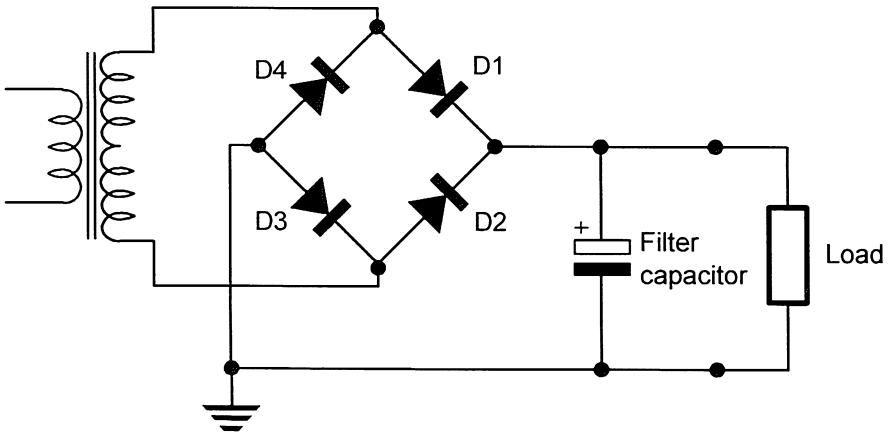
Section 4

1. To smooth the pulsating DC output of a rectifier.

2. (a)



(b)



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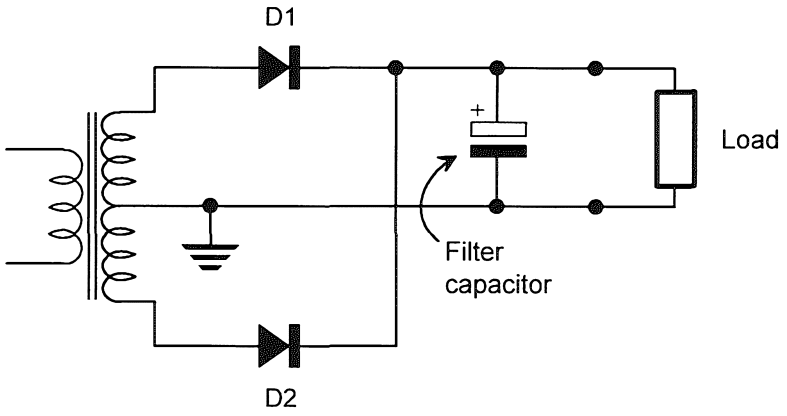
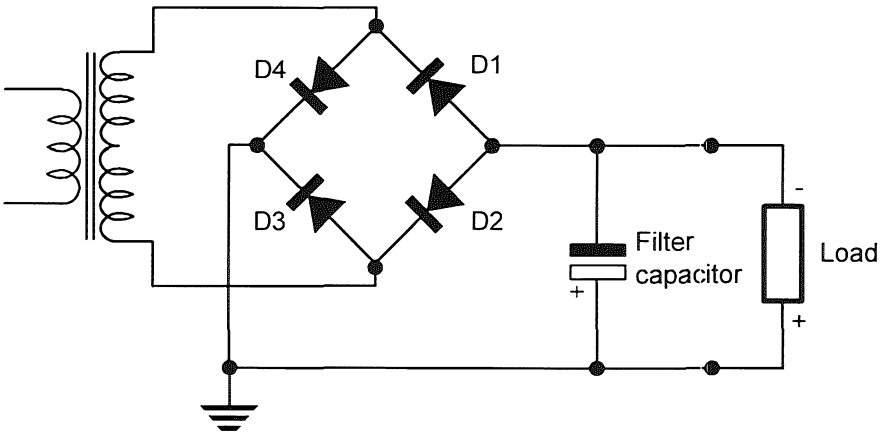
Section 4 (continued)

2. (c)



(d)



3. Because the value of filter capacitors is usually large (eg ≥10,000μF) and such values are not possible with other types of capacitors.

4. When all of the diodes are turned off (that is, when none of them are conducting).

5. 20ms

6. 50Hz

7. 18V

Section 4 (continued)

8. 1.25Vp-p

9. 17.375V

10. $\% \, ripple = \frac{Vout_{(ripple)(RMS)}}{Vout_{(DC)}} \times 100$

    $\% \, ripple = \frac{442mV}{17.4} \times 100$ [Note: A ripple of $1.25V_{P-P}$ is $442mV_{RMS}$]

    Ripple percentage = 2.54%

11. A power supply with a ripple percentage of 1.3% is better than one with 2.54% because the smaller the ripple percentage the better.

    [Note: The smaller the ripple percentage, the smaller the ripple voltage is compared to the maximum output voltage. This means that the output voltage is more smooth.]

12. 17.375V

13. 18V

14. The size of the load resistance
    The size of the filter capacitance
    The frequency of the pulsating DC

    [Note: Half-wave rectifiers have a 50Hz pulsating DC and full-wave rectifiers have a 100Hz pulsating DC.]

15. Full-wave rectifiers are used in preference to half-wave rectifiers
    Large values of filter capacitance are used

16. half the ripple voltage out of a half-wave rectifier.

17. 0V

18. The maximum output voltage ($Vout_{(max)}$)

19. 10ms

20. 100Hz

21. 15V

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Section 4 (continued)

22. 300mVp-p

23. 14.85V

24. 0.71% Note: Don't forget to convert the ripple voltage to RMS

25. 17V

Section 5

1. Dual rail half-wave rectifier

2. B

3. B and C

4. +12.1V and -12.1V

5. Either open-circuit D2 or open-circuit secondary (below the centre-tap).

6. Leaky C1.

7. Dual rail full-wave rectifier

8. +16.4V and -16.4V

9. Either open-circuit primary or open-circuit secondary winding.

10. Leaky C2

11. Open-circuit on either D1 or D2.

12. Open-circuit C1

Section 6

1. decreases as the load resistance decreases.

2. The ability of a power supply to keep the output voltage constant for changes in the mains voltage.

3. The ability of a power supply to keep the output voltage constant for changes is the load current.

4. Shunt regulation and series regulation.

5. line voltage and load current.

6. line voltage and load current.

7. $\%\ reg = \frac{Vout_{(NL)} - Vout_{(FL)}}{Vout_{(FL)}} \times 100$

   $\%\ reg = \frac{12V - 11.6V}{11.6V} \times 100$

   $\%\ reg = 3.45\%$

8. First, transpose the equation to make $Vout_{(FL)}$ the subject.

   $\%\ reg = \frac{Vout_{(NL)} - Vout_{(FL)}}{Vout_{(FL)}} \times 100$

   $\frac{\%\ reg}{100} = \frac{Vout_{(NL)} - Vout_{(FL)}}{Vout_{(FL)}}$

   $\frac{\%\ reg}{100} = \frac{Vout_{(NL)}}{Vout_{(FL)}} - \frac{Vout_{(FL)}}{Vout_{(FL)}}$

   $\frac{\%\ reg}{100} = \frac{Vout_{(NL)}}{Vout_{(FL)}} - 1$

   $\frac{\%\ reg}{100} + 1 = \frac{Vout_{(NL)}}{Vout_{(FL)}}$

   $\frac{1}{\frac{\%\ reg}{100} + 1} = \frac{Vout_{(FL)}}{Vout_{(NL)}}$

   $\frac{Vout_{(NL)}}{\frac{\%\ reg}{100} + 1} = Vout_{(FL)}$

   $Vout_{(FL)} = \frac{Vout_{(NL)}}{\frac{\%\ reg}{100} + 1}$

Answer continued on next page.

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Section 6 (continued)

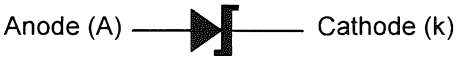
Then solve with the information given:

$$Vout_{(FL)} = \frac{12V}{\frac{7}{100}+1}$$

$$Vout_{(FL)} = 11.21V$$

Section 7

1.



2. See above.

3. The reverse breakdown voltage of a rectifier diode is typically between 400V and 1000V. The reverse breakdown voltage of a zener diode is typically between 3.3V and 33V.

4. 0.6V (like rectifier diodes!).

5. Reverse biased

6. The "zener voltage" or the "zenering voltage".

7. 0.6V (because the zener diode in the circuit is forward biased so it operates just like a normal diode)

8. 8.4V

9. 4.7V

10. $V_R = E - V_{ZD}$

$$V_R = 9V - 4.7V$$

$$V_R = 4.3V$$

11. $I = \frac{V_R}{R}$

$$I = \frac{4.3V}{820\Omega}$$

$$I = 5.24mA$$

Section 7 (continued)

12. $P_R = I^2 \times R$ or $P_R = I \times V_R$ or $P_R = \frac{V_R}{R}$

$P_R = 5.24mA^2 \times 820\Omega$ $P_R = 5.24mA \times 4.3V$ $P_R = \frac{4.3V^2}{820\Omega}$

$P_R = 22.55mW$ $P_R = 22.55mW$ $P_R = 22.55mW$

13. $P_{DZ} = I \times V_{ZD}$

$P_{DZ} = 5.24mA \times 4.7V$

$P_{DZ} = 24.66mW$

14. $P_T = P_R + P_{ZD}$

$P_T = 22.55mW + 24.66mW$

$P_T = 47.21mW$

15. 12V (The same as the zener diode's zenering voltage.)

16. The transformer's secondary voltage is 15V (RMS). So, . . .

$Vs_{(pk)} = V_{RMS} \times 1.414$

$Vs_{(pk)} = 15V \times 1.414$

$Vs_{(pk)} = 21.2V$

The unregulated DC input voltage to the shunt regulator is the same as the output voltage of a filtered bridge rectifier. So, . . .

$Vin_{(DC\ unregulated)} = Vs_{(pk)} - 1.2V$

$Vin_{(DC\ unregulated)} = 21.2V - 1.2V$

$Vin_{(DC\ unregulated)} = 20V$

17. $V_{RS} = V_C - V_{DZ}$

$V_{RS} = 20V - 12V$

$V_{RS} = 8V$

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Section 7 (continued)

18. $I_{RS} = \frac{V_{RS}}{R_S}$

$I_{RS} = \frac{8V}{100\Omega}$

$I_{RS} = 80mA$

19. $I_{RL} = \frac{V_{RL}}{R_L}$

$I_{RL} = \frac{12V}{330\Omega}$

$I_{RL} = 36.36mA$

20. $I_{DZ} = I_{RS} - I_{RL}$

$I_{DZ} = 80mA - 36.36mA$

$I_{DZ} = 43.64mA$

21. $P_{RL} = I_{RL} \times V_L$ or $P_{RL} = I_{RL}^2 \times R_L$ or $P_{RL} = \frac{V_{RL}^2}{R_L}$

$P_{RL} = 36.36mA \times 12V$ $P_{RL} = 36.36mA^2 \times 330\Omega$ $P_{RL} = \frac{12V^2}{330\Omega}$

$P_{RL} = 436.4mW$ $P_{RL} = 436.4mW$ $P_{RL} = 436.4mW$

22. $P_{DZ} = I_{DZ} \times V_{DZ}$

$P_{DZ} = 43.64mA \times 12V$

$P_{DZ} = 523.7mW$

23. $P_{RS} = I_{RS} \times V_{RS}$ or $P_{RS} = I_{RS}^2 \times R_S$ or $P_{RS} = \frac{V_{RS}^2}{R_S}$

$P_{RS} = 80mA \times 8V$ $P_{RS} = 80mA^2 \times 100\Omega$ $P_{RS} = \frac{8V^2}{100\Omega}$

$P_{RS} = 640mW$ $P_{RS} = 640mW$ $P_{RS} = 640mW$

24. 14V [The input voltage to the shunt regulator must be at least 2V bigger than the output voltage.]

Section 7 (continued)

25. The zener diode will turn off and the circuit will no-longer regulate the output voltage.

26. 1W [Note: The series resistor dissipates 640mW and 1W is the closest higher value.]

27. 1W [Note: Although a ¾W diode would be appropriate when the 330Ω load is connected, the worst case power dissipation (which occurs when there's no load, is 960mW so a 1W rating for the zener diode is better.]

28. 9.1V

29. $P_{DZ} = I_{DZ} \times V_{DZ}$

$P_{DZ} = 13.83mA \times 9.1V$ (Note: You'll have to perform several calculations to obtain the zener diode's current.)

$P_{DZ} = 125.8mW$

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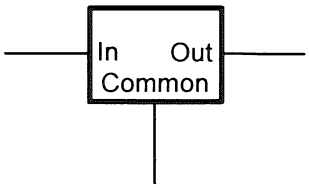
Section 8

1.



2. +5V

3. -24V

4. 7V

5. 12V

6. $I_{RL} = \frac{V_{RL}}{R_L}$

   $I_{RL} = \frac{12V}{210\Omega}$

   $I_{RL} = 57.14mA$

   $P_{RL} = I_{RL} \times V_{RL}$

   $P_{RL} = 57.14mA \times 12V$

   $P_{RL} = 685.7mW$

7. 24.25V

8. $P_{Reg} = I_{Reg} \times (Vin_{(Reg)} - Vout_{(Reg)})$

   $P_{Reg} = 57.14mA \times (24.25V - 12V)$

   $P_{Reg} = 700mW$

9. Use a transformer that has a smaller secondary voltage. [This would reduce the voltage on the input of the regulator which in turn would reduce the voltage across it and so the power it dissipates would be reduced.]

10. 1.25V

11. $Vout = 1.25\left(\frac{R2}{R1} + 1\right) + 50\mu A \times R2$

$Vout = 1.25\left(\frac{2k\Omega}{220\Omega} + 1\right) + 50\mu A \times 2k\Omega$

$Vout = 12.71V$

12. 2V

13. The minimum allowable difference between the 3-terminal regulator's input and output voltages for reliable operation.

LIMITING VALUES

In accordance with the Absolute Maximum Rating System (IEC 60134).

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_{RRM}	repetitive peak reverse voltage		–	100	V
V_R	continuous reverse voltage		–	100	V
I_F	continuous forward current	see Fig.2; note 1	–	200	mA
I_{FRM}	repetitive peak forward current		–	450	mA
I_{FSM}	non-repetitive peak forward current	square wave; T_j = 25 °C prior to surge; see Fig.4			
		t = 1 μs	–	4	A
		t = 1 ms	–	1	A
		t = 1 s	–	0.5	A
P_{tot}	total power dissipation	T_{amb} = 25 °C; note 1	–	500	mW
T_{stg}	storage temperature		−65	+200	°C
T_j	junction temperature		–	200	°C

Note

1. Device mounted on an FR4 printed-circuit board; lead length 10 mm.

ELECTRICAL CHARACTERISTICS

T_j = 25 °C unless otherwise specified.

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_F	forward voltage	see Fig.3			
	1N4148	I_F = 10 mA	–	1	V
	1N4448	I_F = 5 mA	0.62	0.72	V
		I_F = 100 mA	–	1	V
I_R	reverse current	V_R = 20 V; see Fig.5		25	nA
		V_R = 20 V; T_j = 150 °C; see Fig.5	–	50	μA
I_R	reverse current; 1N4448	V_R = 20 V; T_j = 100 °C; see Fig.5	–	3	μA
C_d	diode capacitance	f = 1 MHz; V_R = 0 V; see Fig.6	–	4	pF
t_{rr}	reverse recovery time	when switched from I_F = 10 mA to I_R = 60 mA; R_L = 100 Ω; measured at I_R = 1 mA; see Fig.7	–	4	ns
V_{fr}	forward recovery voltage	when switched from I_F = 50 mA; t_r = 20 ns; see Fig.8	–	2.5	V

THERMAL CHARACTERISTICS

SYMBOL	PARAMETER	CONDITIONS	VALUE	UNIT
$R_{th(j-tp)}$	thermal resistance from junction to tie-point	lead length 10 mm	240	K/W
$R_{th(j-a)}$	thermal resistance from junction to ambient	lead length 10 mm; note 1	350	K/W

Note

1. Device mounted on a printed-circuit board without metallization pad.